

ADVANCED OHMIC HEATING FOR RICE COOKING:  
QUALITY FACTOR ASSESSMENT

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE  
UNIVERSITY OF HAWAI'I AT MĀNOA IN PARTIAL FULFILLMENT  
OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE  
IN  
FOOD SCIENCE

April 2018

BY

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## ACKNOWLEDGEMENTS

I would like to thank everyone who has helped me to complete this thesis. First and foremost, I would like to convey my heartfelt gratitude and appreciation for my thesis adviser and chairperson, **Dr. Soojin Jun**, for encouraging and pushing me to pursue my graduate degree. Without your unlimited support and guidance, I wouldn't have been able to realize my potential as a graduate student and researcher. You have encouraged me to do my best and to be positive always, and I was able to achieve the breakthroughs in my academic life and broaden my knowledge in food science under your mentorship.

My sincere thanks also go to **Dr. Samir Khanal**, who is my committee member, who had given me invaluable advice on my thesis writing, he had given me a ready consent when I had trouble in organizing a committee. My research advanced to the right path because of his help and guidance.

**Dr. Yong Li**, who has introduced me not only to knowledge but also to the appreciation of the world of food microorganism, thank you for your guidance, patience, and support. Your trust me has motivated me to become a better and more responsible researcher. Your class had been nothing but wonderful, and I was amazed by your passion and dedication.

**My parents and family** are who gave me life, boundless love, and words of encouragement. My parent made me only focus on research without any financial problem both on tuition and living cost. I would like to thank my parents and family for their love and support throughout this journey. I also thank **my friends** for being my cheerleaders and sharing this adventure with me.

I am especially thankful to **Sean Francis**, who helped me to design and fabricate the ohmic heater and taught me a lot about food engineering, and **Taiyoung Kang**, who trained and taught

me lab techniques when I was just starting my experiments. Lastly, all of the **research group members** at Food Processing Laboratory, who kept me going through rough times and gave me inspiration about research are deserve thanks from me.

## **Abstract**

Conventional thermal processing of foods containing particulates significantly relies on several heat transfer steps, including conduction and convection, which usually take longer cooking times for the solid-liquid mixture foods and tend to be overly conservative ensuring microbial safety, thus compromising quality. Rice is one of the world's biggest cereal crops next to wheat and maize and is one of the most important staple foods for the world population. Asian people consume cooked rice at almost every meal. Existing methods of cooking are about 10-15% thermally efficient. The ever-increasing population will need more amount of energy and water to be spent on rice cooking. Advanced food processing technologies such as ohmic heating and microwave heating have been developed in the last few decades as alternatives to conventional processing methods. The advanced technologies could contribute to shortening processing times, energy savings, and high-quality safe food. The microwave heating has been employed to cook rice and can reduce the cooking time by more than 40% compared to the conventional cooking method. However, the energy consumption was nearly doubled. Therefore, a new concept to use ohmic heating for rice cooking has been extensively evaluated. This technology was an attractive alternative method with high energy transfer efficiency, time savings, and high quality of purpose.

In this study, an alternative cooking method that offers both high energy efficiency and short cooking time was developed, and a static ohmic heater was designed and fabricated to heat treat rice-water mixtures. The energy consumption, textural characteristics of rice, and simulation of the electrical field in ohmic heater were investigated. Two types of rice were used in this study: white rice and brown rice respectively. The electrical conductivities of rice-water mixtures at various volume ratios were measured during the rice cooking process. The endpoint of rice cooking

by using ohmic heating was identified. The results showed that the rice cooked by the ohmic heating method has significantly different textural properties from rice cooked by an electric rice cooker. The magnitude of texture difference was dependent on the type of rice. The electrical conductivities of white rice, and the brown rice mixture were approximately 0.03-0.08, 0.04-0.1, 0.06-0.12 S/m at volume ratios of 1:0.8, 1:1.2, 1: 1.5 and 0.025-0.16, 0.032-0.2 S/m at volume ratios of 1:1.5 and of 1:2 respectively. The research also found that ohmic heating required a cooking time of around 17-18 min. The estimated amount of energy consumed by the ohmic heating process was about 1/4 of the total energy consumed by electric rice cooker. The developed ohmic heating technique showed a great potential over the conventional electric cooker regarding the high energy efficiency, shorter cooking time, and lower water usage.

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## **Chapter 1**

### **INTRODUCTION**

The conventional thermal processing of food products has been most commonly recognized as a simple and effective way to cook food. Rice is one of the world's cereal crops next to wheat, and it is an essential source of food for the major portion of the world's population. Existing methods of cooking are about 10-15% thermally efficient. The energy and water required by rice cooking would be increased due to the increase in population (Shinde & Vijayadwhaja, 2013). Moreover, excessive thermal treatment for processing food products has frequently caused severe deterioration in quality aspects such as texture, color, flavor, and the destruction of bioactive compounds (Choi et al., 2006). Minimizing processed food products that retain their fresh and nutritional qualities has received considerable attention from customers in recent years (Nguyen & Choi, 2012). To meet rising demands from customers and the trend of modern lifestyle to shorten processing times, food engineers and scientists have enthusiastically endeavored to explore new technologies to replace conventional cooking methods. Alternatives to conventional cooking methods such as microwave heating and ohmic heating have been widely investigated and developed. Rice cooking using ohmic heating was able to obtain comparable food quality in a shorter processing time and with less energy consumption (Kanjapongkul, 2017). Moreover, the emerging advanced food processing technologies have provided excellent advantages such as a rapid heating, shorter time consumption, uniform temperature distribution, and superior energy efficiency close to 100% (Jun and Sastry, 2007; Salengke and Sastry, 2007). Despite the development of these advanced food processing technologies, most of the cooking methods still

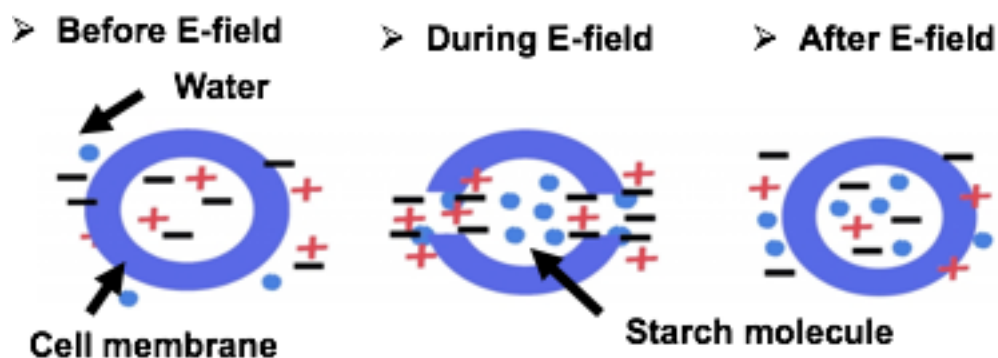
have low thermal efficiency as the rapid increase of people which will need more amount of energy and water to be used for cooking purposes (Shinde and Vijayadwhaja, 2013).

Microwave (MW) heating is a result of the interaction between the alternating electromagnetic field and the dielectric material (Orfeuil, 1987). In the same report, Wang et al., (2009), explained that microwave heating has an interaction with polar water molecules and charged ions within the food. Volumetric heating is produced by the induced frictional energy from the realignment of water molecules and the conductive migration of charged ions in the alternating magnetic field. Microwave heating is gaining popularity over conventional heating owing to its inherent advantages of rapidity and convenience. The frequency of a 2,450 MHz system is widely used in domestic microwave ovens and some industrial applications. The 2,450 MHz systems have the limitation of a small penetration depth of about 1 cm, while the 915 MHz system can penetrate much more in-depth at about 3 cm. However, microwave heating has been intensively used to heat up ready-to-eat (RTE) food since microwaves heat foods in a rapidity and directly (Hossan, Byun, & Dutta, 2010). Microwave heating can be applied to rice cooking with the least cooking time (Lakshmi et al., 2007). The microwave oven is a multi-utility kitchen appliance that can be used for rice cooking. It is suitable for cooking small quantities, especially in households (Juliano, 1985). However, problems associated with microwave heating are numerous, including localized heat zones due to the variation of dielectric, physical, and thermal properties of food components (Pitchai et al., 2012). Lakshmi et al., (2007) reported that microwave heating has been applied to cook rice and can reduce the cooking time by more than 40%. However, energy consumption was nearly doubled compared with the conventional cooking method.

As mentioned earlier, the conventional heating method has been widely considered as an effective and simple way to cook. The cooking methods used have a significant effect on the chemical compositions, physicochemical properties and eating quality of cooked samples (Jittanit and Khuenpet, 2017). Nowadays, the most common home appliance for rice cooking is the electrical rice cooker due to its conventional heating concepts. In an automatic rice cooker, heat is regulated by a thermostat which is a temperature sensor, coupled with a microswitch, which switches off the heater when the water is completely absorbed and the temperature begins to rise rapidly. The temperature of the rice starts to decrease significantly after the heater is turned off. Therefore, the electrical rice cooker switches to “keep warm” mode automatically under the supervision of temperature sensor and control. The electrical rice cooker with “cooking” and “keep warm” modes was introduced, which are most common in countries, such as China and India. The electrical rice cooker worked on the principle of dielectric heating and originated from the military equipment (Juliano & Sakurai, 1985). The heat transfer steps for the mixture of rice and water cooked by the conventional heating method include: the heat is generated by the heater; it is transferred to the container by conduction firstly; then it is transmitted to the water and rice by convection and conduction, respectively. It shows that several heat transfer steps make a long cooking time for processed rice.

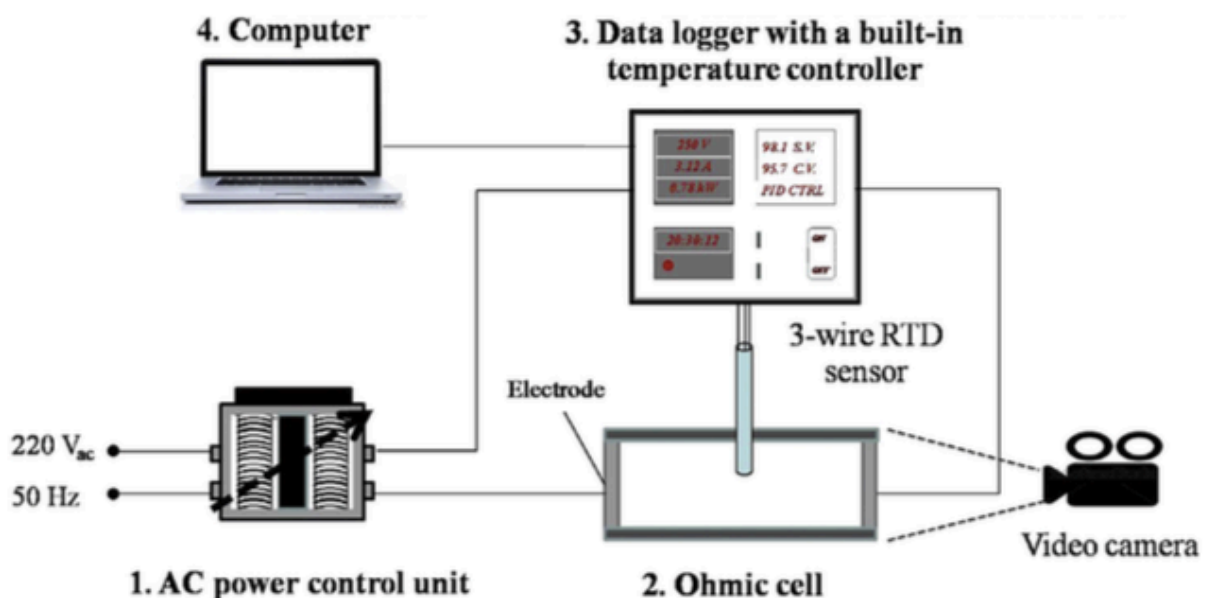
A new concept of advanced ohmic heating for the processing of mixtures between water and rice or multiphase foods has been intensively evaluated to minimize the processing procedures and cooking time. The ohmic heating technology has a significant impact on the heating uniformity with enhanced qualities. For instance, white rice and brown rice processed by ohmic heating

developed by Jittanit and Khuenpet (2017) did not experience any significant different textural characteristics (hardness, chewiness, etc.) but provided shorter cooking time, as compared with the conventional cooking method (electric rice cooker). Also, resolving the uneven temperature distribution is an issue in the conventional thermal processing of foods, which may risk food safety. For ohmic heating, electric field distribution inside the electrode heater was relatively uniform, as reported by Nguyen and Choi (2013). Similar reports also showed that the subject is heated quickly and uniformly by using ohmic heating (Kanjapongkul et al., 2009; Li and Sun, 2002). However, most studies in advanced food processing technologies for different types of rice processes have been aimed at the fundamental understanding of the process with low-energy transfer efficiency and high usage of water. In addition, the aforementioned ohmic heating required specific conditions that substantially relied on the pre-estimation of electrical conductivities and chemical properties of targeted foods (Lee et al., 2015).



**Fig. 1.1.** Electroporation during rice cooking (Modified from Neoelegance, 2018)

The ohmic heating technology has been proposed and tested for the heating uniformity of targeted foods and applied in rice cooking. It was expected that ohmic heating would heated the food quickly and evenly via its current and i internal heating concepts, and that it would also be beneficial for the quality of rice, based on the characteristic of electroporation which contributes to the water diffusion inside the kernels of rice during the cooking and internal heating concept. According to Fig. 1.1, the cell electroporation is defined as the formation of pores in cell membranes due to the presence of an electric field leading to the enhancement of membrane permeability and diffusivity (An & King, 2007). Kanjanapongkui (2017) have attempted to develop a static ohmic heating heater, coupled with stainless plates as two electrodes and voltage transformer (Fig. 1.2). It was validated that water and rice (2.5: 1) were heat treated via electrical current. However, the stainless plates experienced fouling issues due to the application of high voltage and long-term use. There was no clear evidence to test the rice quality between ohmic heating method and conventional heating method. Besides, more types of rice should be applied for ohmic heating.





**Fig. 1.2.** Schematic diagram of an ohmic heating system (Kanjapongkul, 2017)

Therefore, it was necessary to design and fabricate an ohmic heating heater to maximize the electric field strengths and prevent the fouling issues on both sides of electrodes. Titanium was employed instead of stainless plates as two electrodes in this study because it is known that it has high corrosion resistance characteristic. This new ohmic heating cell could result in better thermal distribution and deliver maximum energy to multiphase foods and prevent the fouling issue on the electrodes. Concerning the rice quality assessment, rice textural analysis could be conducted to compare different types of rice processed by ohmic heating and electric rice cooker. Accordingly, the effectiveness of the ohmic heating on rice cooking with the low ratio of rice to water (1:0.8) should be examined in order to decrease the usage of water in the rice cooking. In addition, the energy consumption of ohmic heating during rice cooking would be validated. This method could provide a practical solution or an attractive alternative method for a uniform thermal treatment of rice cooking with low energy consumption and high quality.

Thus, this study was intended to accomplish the following specific objectives:

**Objective 1:** Design and fabricate a static ohmic cell equipped with two electrodes to process the water and rice mixture through ohmic heating.

**Objective 2:** Improve the ohmic heating cell, rice quality by evaluating its effectiveness in rice cooking under varying electric field strengths and textural analysis of cooked rice on the different volume ratios of rice to water.

**Objective 3:** Validate the heating uniformity in rice cooking by using a numerical simulation to analyse the electrical field and temperature distribution, and to estimate the energy consumption by the conventional and ohmic heating method.

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## **Chapter 2**

### **LITERATURE REVIEW**

#### **2.1 Introduction**

This section presents the basic concepts of emerging thermal food processing technologies for rice cooking and introduces the domestic appliance used in rice cooking. Moreover, the cooking method and utensils (container) significantly affect on the chemical compositions, the physicochemical properties, and the sensing and tasting quality of cooked rice. Ohmic heating is a novel thermal process involving the internal heat generation by applying an electrical current through a food product. Developed ohmic heating technologies have been applied to various food processing, such as extraction, pasteurization, and sterilization. Existing methods of cooking are about 10-15% thermally efficient. The ever growing population will need more energy to be spent on the cooking purpose. Regarding rice cooking, the high usage of water is also an issue. Therefore, the ohmic heating technology has a high potential to enhance overall qualities of food production due to its high energy transfer efficiency. The various applications of food processing technologies for rice cooking from recently published literature will be discussed.

#### **2.2 Existing thermal food processing technologies**

##### **2.2.1 Ohmic heating**

Ohmic heating (OH) is a novel thermal processing that applies electrical current into the food sample to directly generate heat inside the food. In ohmic heating, there is no need to transfer

heat through solid-liquid interfaces or inside solid particles once the energy is dissipated directly into the foods (Knirsch, Alves dos Santos, Martins de Oliveira Soares Vicente, & Vessoni Penna, 2010). Currently, ohmic heating is used as a thermal method to preheat, to blanch and to pasteurize and sterilize fruit and meat products (Marcotte, Ramaswamy, & Sastry, 2014). In the earlier applications, the use of low alternating current frequencies in the range of 50-60 Hz was found to be disadvantageous, as it lead to increased electrochemical reactions and electrode erosion (Ruan et al., 2001). Direct contact of the food with the electrodes is regarded as a critical aspect of the application of ohmic heating (Jaeger et al., 2016). The subsequent technical improvements of the ohmic heating process concerning the electrode materials being used such as titanium and optimized alternating current frequencies have been widely promoted and studied (Pataro et al., 2014; Samaranayake, Sastry, & Zhang, 2005). Ohmic heating has made a considerable contribution to uniformity improvement in foods (Nguyen et al., 2013). Energy conversion efficiency during ohmic heating process is remarkably high close to 100%, and has uniform temperature distribution (Jun and Sastry, 2005; Salengke, 2000). Moreover, it has been essential to investigate the non-thermal effect (electroporation) of OH on the permeability of cell membrane with reducing heat generation (Lee and Jun, 2011). Ohmic heating depends on electrical conductivities of foods, and it is desirable that liquids and particles should have equal conductivities to achieve uniform heating (Wang and Sastry, 1993). Kanjanapongkul (2017) pointed out that the advantages of ohmic heating is the electrophoretic force with electro-osmosis under high-intensity electric field in ohmic heating, which can enhance the moisture diffusion into rice grains and accelerate the diffusion process during rice cooking. Another advantage is that the food does not come into contact with hot surfaces. It is also possible to mainly prevent the

formation of unwanted layers of biological, organic or inorganic composition which also called fouling issue (Goullieux & Pain, 2005).

### **2.2.2 Microwave heating**

Recently, microwave heating has been applied to cooked rice and can reduce the 40% cooking time compared with conventional heating method (Lakshmi et al., 2007). Microwave (MW) heating is a result of interaction between the alternating electromagnetic field and dielectric material (Orfeuill, 1987). Microwaves (MW), which are a part of electromagnetic spectrum and have frequency range between 300 MHz and 300 GHz, have been successfully employed to various food processing, including tempering or thawing of bulk frozen foods (meat, fish, and others), cooking of bacon and sausage, and drying of pasta and vegetables (Bengtsson and Ohlsson, 1974; Hulls and Shute, 1981; Hulls, 1982; Jones, 1992; Schiffmann, 1992). Two frequencies, 2450 and 915 MHz, are allocated by the US Federal Communications Commission for MW heating applications (Decareau, 1985; Metaxas and Meredith, 1983). 2450-MHz are widely used in domestic MW ovens and some industrial applications. 2450-MHz systems have the limitations of small penetration depth at 1 cm and multi-mode cavities, causing non-uniform and unpredictable heating patterns in food packages. In general, 915-MHz microwaves can penetrate much deeper at 3 cm in foods, and therefore may provide more uniform heating (Mudgett, 1989). Since microwave heating has complete interaction with polar water molecules and charged ions within the food, volumetric heating can be produced by friction energy (Wang et al., 2009). Microwave heating is effective for reducing come-up-time and better preserves thermo-labile constituents (Coronel et al., 2003). To understand the interaction between electromagnetic field and food, research for measuring dielectric properties of food should be conducted (Buffler, 1993). The

conversion efficiency of electrical to microwave energy is only about 50%. However, the microwave cooking offers the least cooking time of around 15 to 22 min for rice cooking (Lakshmi et al., 2007).

### **2.2.3 Induction heating**

Induction heating is a complicated process of electromagnetic-temperature-stress multi-field coupling process. It has been widely used in industrial products such as crankshafts, sprockets, steel tubes and slabs (Jianliang et al., 2018). The technique of heating by electromagnetic induction is well established and is invaluable for industries engaged in heat treatment or hot working of metals due to the high efficiency, precise control and low pollution properties (Villacis et al., 2015). Induction heating was first applied to home appliances in mid-1970s. Therefore, lots of research into inducting heating appliances have been performed. An induction cooker presents several advantages. There are two significant advantages of the induction cooker which has been concluded in (Barragen, et al., 2008), namely, energy saving and safety enhancement. Although, the previous research has proved that enameled cast iron material as the most efficient material for producing pots could allow having an efficiency higher than 80%, it is still lower than the energy conversion efficiency during the ohmic heating process which is remarkably high close to 100% (Jun and Sastry, 2005). Moreover, the price of existing induction cookers on the market is more than doubled that of conventional cookers.

### **2.2.4 Conventional heating method (electric rice cooker)**



An electric rice cooker is commonly for domestic use. Nowadays, the most common appliance for rice cooking is the electric rice cooker. The heat is generated by converting electrical energy to thermal energy at the heating plate, and then, the heat is transferred to the pot and the water-rice mixture, respectively, through the heat conducting and convection mechanisms (Tribeni Das, 2004). This method has been improved over the years to make the quality of the cooked rice acceptable. In the automatic rice cooker, heat is regulated by a thermostat coupled with a microswitch, which switches off the heater when the water is completely absorbed and the temperature begins to rise rapidly. The temperature of the rice decreases quickly after the heater is switched off. Therefore, cookers with ‘cooking’ and ‘keep warm’ modes were introduced which are common in countries like India. The thermal efficiency of the electric rice cooker is limited due to its technically conceptual design which is indirect heating (Jittanit, 2017). Roy et al. (2010) pointed out that the cooking properties of rice depended on the forms of rice, the water-rice ratio, and the preset cooking mode. It is well known that the brown rice requires much longer cooking time and water-rice ratio than white rice; as a result, it is inconvenient and not compatible with the modern lifestyle that does not want to spend long time for preparing food.

## **2.3 Characteristic of ohmic heating for rice cooking**

### **2.3.1 Ohmic heating for cooking rice**

According to An and King (2007), ohmically heated rice starch show most significant decrease in enthalpy which is needed energy since the significant extent of pre-gelatinization through ohmic heating. The conventionally heated rice starch became rigid due to starch-chain interactions. According to Kanjanapongkul K (2017), ohmic heating was proposed as an

alternative method to cook Jasmine rice fast compared with the electric rice cooker. The electrical conductivity of mixtures of Jasmine rice sample and water at various ratios was measured, and Jasmine rice grain's swelling behavior, the water diffusion, energy consumption were investigated. The results revealed that the application of electrical field enhances the quantity of water diffused into the rice grain. The ohmic heating process saved more than 70% of the total energy required for a commercial electric rice cooker. However, the rice cooking time by using ohmic heating at the 30V/cm electric field strength was slightly longer than time taken by the electric rice cooker. The diversity of rice and higher electrical field strength should be analyzed in the future studies. In another study has been conducted by Jittanit and Khuenpet (2017), four types of rice samples including white rice of two varieties (KDML105 and Sao Hai), and brown rice and germinated brown rice of one variety (KDML105) were used. The pre-estimation of the electrical conductivity is important to properly design an ohmic heater for rice cooking. However, it was difficult to measure the electrical conductivity of rice grains due to the small size and curvature of a rice grain. Analysis of an equivalent electric circuit of the food mixture was thus used as an indirect method to determine the electrical conductivity of the rice grain. The electrical conductivity of water and mixture between water and rice both are temperature dependent. The mixing ratio of Jasmine rice to water used was 2.5: 1, with 150-gram samples in the study under low electric field strength. However, during the rice cooking, the water was replaced with the salt solution, using the ohmic heating method, because the electrical conductivity of pure water was too low. Stainless plates were used as electrodes coupled at the ohmic cell, which has been considered as a low ability of corrosion resistance plates. In conclusion, the outcome of all studies revealed that it is possible to apply ohmic heating in the cooking of rice. More studies should be a focus on the optimized operation parameters for ohmic heating, such as voltages and electric field strength. A scaled

ohmic cell should be developed to heat up more samples.

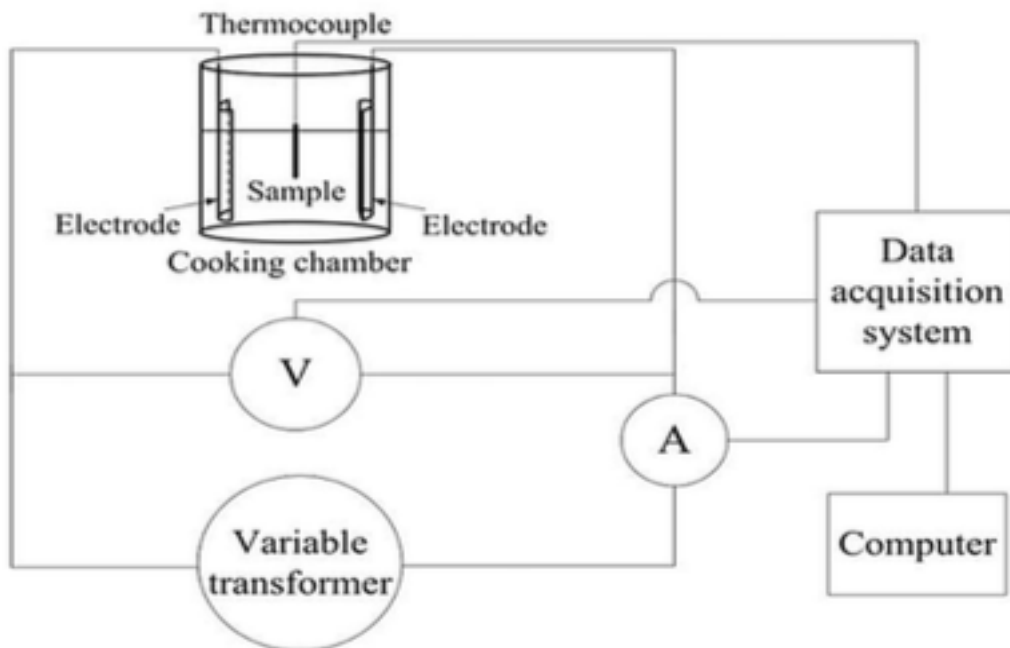
### **2.3.2 Rice grain's swelling behavior during the cooking process**

According to Kong et al., (2015), the crystalline structure of starch granules was destructive due to the breakage of the hydrogen bond when the temperature reaches the gelatinized point, resulting in the increase of volume. Wani et al., (2012) conducted another study, and it was explained that the movement of water molecules to the exposed hydroxyl groups of amylose and amylopectin cause the granule swelling and solubility. Vandeputte et al, (2003) reported that structural aspects of rice starches, for example, amylopectin's swelling distribution had a significant impact on the swelling behavior. Another study of the rice grain's swelling behavior during ohmic heating was conducted by Kanjanapongkul, (2017), who prepared at a ratio of water to rice grains of 2.5:1 by bulk volume sample. In this study, rice-water mixtures were ohmic heated from room temperature to 100 °C under a constant electric field of 20V/cm. A video camera was used to monitor the change in the rice layer height during the whole heating process. The results showed that the slow swelling behavior of rice grains at low temperature. However, when the temperature was higher than 80 °C after 1000 seconds, the rice grains expanded much faster. The heating rate from 60 to 80 °C was relatively fast, but started to drop after 80 °C, which was the point where the rice grains expanded more quickly. Similar results were found by Kemp and Fryer (2007), Jasmine rice, is a long grain variety that has a gelatinization temperature of around 70 to 80 °C.

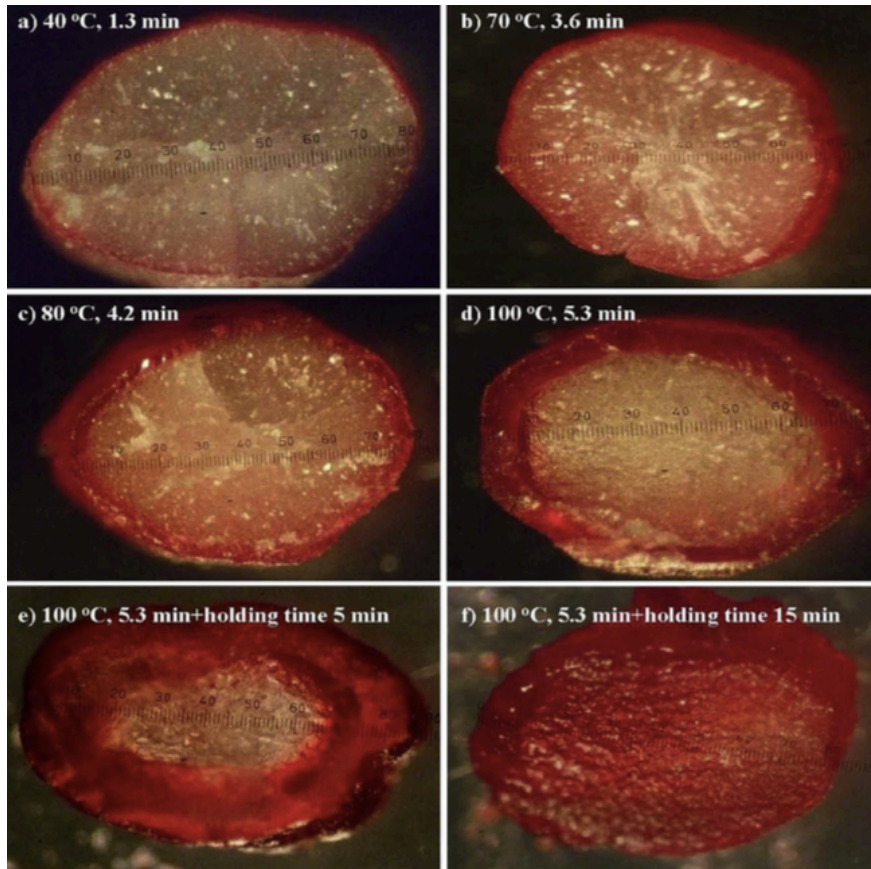
### **2.3.3 Determination of electrical conductivity of the mixture**

Electrical conductivity is an important property of the food sample for ohmic heating since the food sample in the ohmic cell is in direct contact with the two electrodes during the process. It could be explained that it is a prerequisite for the corresponding heat development (Wang & Sastry, 1993). The determination of the electrical conductivity of white rice grains is also very important to properly design an ohmic heater or ohmic heating cell. The electrical conductivity is temperature-dependent. It changes during the heating process when the temperature increases. The cell structures are lysed when the heat releases ions, which results in a significant change in the electrical conductivity of the food and thus it affects the process of ohmic heating (Castro, Teixeira, Salengke, Sastry, & Vicente, 2003; Wang & Sastry, 1997a, 1998). According to the previous study by Kanjanapongkul (2017), it was difficult to measure the electrical conductivity of rice grain; thus, the analysis of an equivalent electric circuit of the mixture between the rice grains and water was used as an indirect method to determine the electrical conductivity. To calculate the electrical conductivity of the rice grain, the electrical conductivities of water and the mixture between the rice grains and water were determined. The results showed that electrical conductivity of water and that of the mixtures of water and rice are influenced by temperature. There is a linear relationship between the electrical conductivity of water and that of rice. A similar measuring method was used in Mok et al., (2017) and Jittanit & Khuenpet, (2017), the equation of  $\sigma$ , electrical conductivity =  $IL/(VWH)$ , where I and V are the electric current and voltage, respectively, while L, W, and H are the distance between electrodes, width and height of the mixture, respectively was used to measure the electrical conductivity of food (see Fig. 2.1). According to the Sastry and Palaniappan (1992), the electrical conductivities of mixtures of liquid and multiple particles within a static heater increase with temperature. The study apparently shows that from the beginning of the ohmic heating period at the temperature around 30 °C until reaching the temperature of around

60-90 °C, the electrical conductivities increase along the temperature. However, Jittanit and Khuenpet, (2017) reported that the trend of electrical conductivities of four different types of rice samples changed to be significantly decreased after reaching the temperature of about 60-90 °C. A similar result also reported by Wang and Sastry, (1997b), the starch solution had a rise in electrical conductivity as the temperature increased, but the conductivity decrease again as the level of gelatinization increased. This phenomenon should be related to the starch gelatinization. The temperature of starch gelatinization is depends on the types of rice (Roy et al., 2010).



**Fig. 2.1.** Schematic diagram of the ohmic heating apparatus for electrical conductivity measurement (Jittanit & Khuenpet, 2017)



**Fig. 2.2.** Diffusion of water into rice grains during ohmic heater under 40V/cm

(Kanjapongkul, 2017)

#### **2.3.4 Water diffusion during the cooking process**

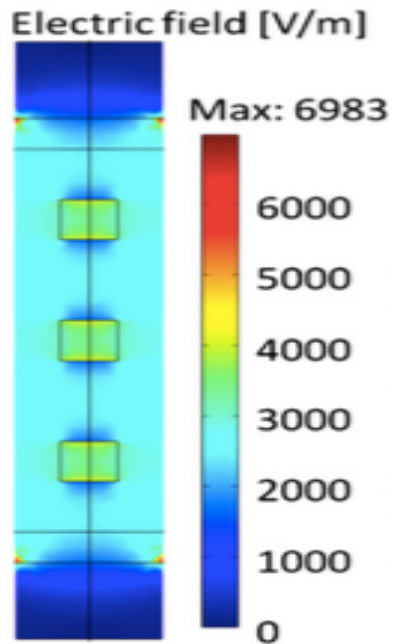
Cooking rice is a process in which a mixture of rice and water is heated, leading to the gelatinization of rice starch (Shinde et al., 2014). The end point of cooking was identified by using parallel glass plate method as proposed by Desikachar and Subramanyan (1961). In this method, the rice samples periodically drawn during cooking were pressed in between two small glass plates, and when there was no hard core observed, then the rice was considered to be completely cooked.

Similar results were reported by Lakshmi et al., (2007). The cooking process is complete when the water diffuses into the whole rice grain, and no white core is observed. Water diffusion is considered as one of the necessary conditions for the determination of the endpoint of rice cooking (Bello et al., 2007). The previous study conducted by Kanjanapongkul, (2017) showed that water slowly diffused into rice grains in the beginning. Beyond the gelatinization point at around 80 °C, water diffused slightly more rapidly into rice grains (see Fig. 2.2). Increasing the electric field strength increased the heating rate, shortened the time required to heat the rice to 100 °C and accelerated water diffusion. The increase of the supply of electric energy of the electrical field strength might be another factor that enhanced the diffusion of water into the rice grain and accelerated diffusion process. Another previous research also agreed with the results, showing that the electric field and temperature enhanced the diffusion coefficient and effective ionic mobility (Kusunadi and Sastry, 2012). Briffaz et al., (2014) reported the water transport was associated with starch gelatinization.

### **2.3.5 Simulated electric field and temperature distribution under ohmic heating**

Electric field distribution is essential when designing the performance of ohmic heaters since it affects the heating uniformity and energy efficiency of the developed heater. In the previous studies (Nguyen et al., 2012), the detailed analyses of electric field distribution inside the ohmic heater at a stationary state were conducted by numerical simulation (COMSOL 3.5, COMSOL, Inc., Palo Alto, CA). A similar method also used by Hyun et al., (2015), to analyze the electric field distribution in the heater by using COMSOL Multiphysics software. Both of the simulated results of electric field distributions showed that for ohmic heating, electric field

distribution inside the electrode heater was relatively uniform. The results of the electric field distribution are given in Fig. 2.3 (Nguyen, et al., 2013).



**Fig. 2.3.** Distribution of the electric field in the heater under ohmic heating

(Nguyen, et al., 2013)

## 2.4 Conclusion

The present review has demonstrated the successful application of the ohmic heating method for various types of rice cooking under the limited conditions. Ohmic heating was considered as an attractive alternative method for rice cooking due to its various advantages, including there is no heating medium being required and the subject being heated quickly and uniformly. Most importantly, it is nearly 100% energy transfer efficient compared with other existing methods of cooking, which are about 10-15% thermally efficient. The ever-rising population will need more amount of energy to be spend on cooking food and the modern lifestyle



that does not want to spent a long time for preparing food. In addition, the research mentioned in the previous part of this paper has shown that the ohmic heating could simplify the food processing procedure with the reduction of processing time and energy consumption, particularly in rice cooking, as compared with the conventional heating method.

Although the attractive heating method provides significant advantages in a variety of food processing areas, the limitation of food products and the cooking conditions depending upon electrical conductivity, and the chemical properties of raw food material should still be take into account in the research. A pre-estimation of electrical conductivities of food necessary to heat up the purposes of ohmic heating. Foods that have lower electrical conductivities will be heated slower than those of higher electrical conductivities. There was no apparent evidence to compare and prove some quality aspects between food products processed with conventional cooking methods and those processed with ohmic heating. Furthermore, the majority of ohmic heating technology introduced by previous researchers was evaluated on lab scale systems.

Therefore, it is essential to concretely investigate parameters that can affect the quality of rice using ohmic heating such as electrical conductivities of rice and the ratio of rice to water during rice cooking. Additionally, to practically apply ohmic heating technology in commercial sites for the processing of rice, the future research should be conducted in a large-scale system, and a more precise numerical modeling should be used. It is necessary to develop methods to increase the electrical conductivities of the mixture between water and rice instead of adding the salt solution in the previous study.

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## **Chapter 3**

### **Advanced ohmic heating for rice cooking: quality factors assessment**

#### **3.1 Introduction**

Rice is an important source of food for a significant portion of the world's population. Thus, efforts are being made to improve the yields of rice crops and also make them more nutritious. Regarding the total energy consumption in the world, about 40%, is used for cooking purposes in the developing world. Existing methods for rice cooking are about 10-15% thermally efficient. The ever-increasing population will need more energy to be spent on rice cooking (Shinde and Vijaydhwaja, 2013). The conventional cooking approach for rice requires a relatively long processing time, high energy, and several procedures to achieve even temperature distribution between water and rice because it substantially depends on convection and conduction for the heat transfer from heating source to the food (Mullin, 1995; Nguyen et al., 2013). Thus more efficient methods of cooking need to be developed. The feasible solutions to achieve the uniform heating with rapidity, high-quality maintenance, high energy transfer efficiency, and time-saving are the advanced ohmic heating method and the microwave heating method.

However, several studies on the thermal processing by using microwave heating showed several inherent problems, such as non-uniform heating or edge overheating with cold spots located in the geometric center. Also, the energy efficiency of microwave heating at 2.45 GHz only go up to 65% (Nguyen et al., 2013; Saltiel and Datta, 1999; Tang et al., 2008; Ramaswamy et al., 1991).

Previous studies on the application of ohmic heating for rice cooking has shown that the ohmic heating technique is an attracting alternative for white and brown rice cooking with the addition of 0.1 M salt solution (Jittanit et al., 2017; Kanjanapongkul, 2017). Ohmic heating takes its name from Ohm's law, the food material heated between electrodes has a role of resistance in the circuit. However, the effectiveness of the ohmic heating heater and the fouling electrodes located in both sides of ohmic heating cell always is a big issue in ohmic heating (Salengke and Sastry, 2007; Sarang et al., 2008). In addition, there was no rice quality factors analysis, such as textural analysis, to compare the rice quality differences between different volume ratios of rice-water mixture in order to achieve the goal of saving the water spent in rice cooking process.

A static advanced ohmic heating heater was designed and fabricated to deliver the maximum electric field strengths and prevent the fouling issues on both sides of electrodes. The advanced ohmic heating technique proposes that mixtures between water and rice are heated via electric current with rapidity and uniformity, which will eventually eliminate the drawbacks of low energy transfer efficiency in conventional heating method and decrease the processing time. The objectives of the study are applying the advanced ohmic heating for rice cooking and test rice textural analysis under low rice to water volume ratio, and also to optimize the effect of the ohmic heating by tuning operation parameters such as voltage and power levels.

## **3.2. Materials and methods**

### **3.2.1 Raw materials**

White rice and brown rice was purchased from the local market, kept at room temperature (28 °C), and used in the experiment without any further treatment. Two types of rice samples were used in this study: white rice (RHEE BROS Co. Ltd., Santa Fe springs, United States), and brown

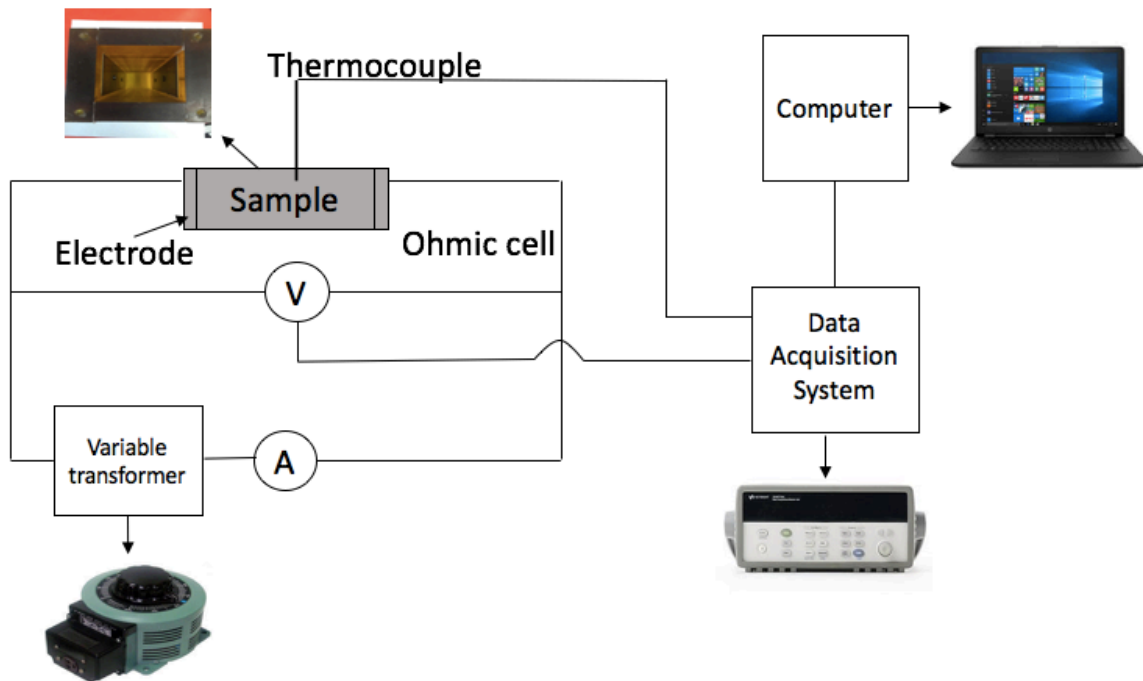
rice (SunFoods Co. Ltd., Woodland, United States). Brown rice is a favorite rice variety in the United States and categorized as non-GMO, gluten-free, and heart healthy. Tap water was used in this experiment because it is generally used in washing and cooking rice. To make sure that there was no variation in the electrical properties of cooking water, a water sample was collected once in a large, clean container. While measuring the electrical conductivity of cooking rice by using ohmic heating, the rice samples were mixed with water at different ratios: 1:0.8, 1:1.2, 1:1.5, and 1:1.5, and 1:1.2 respectively (rice: water).

### **3.2.2 Ohmic heating set up**

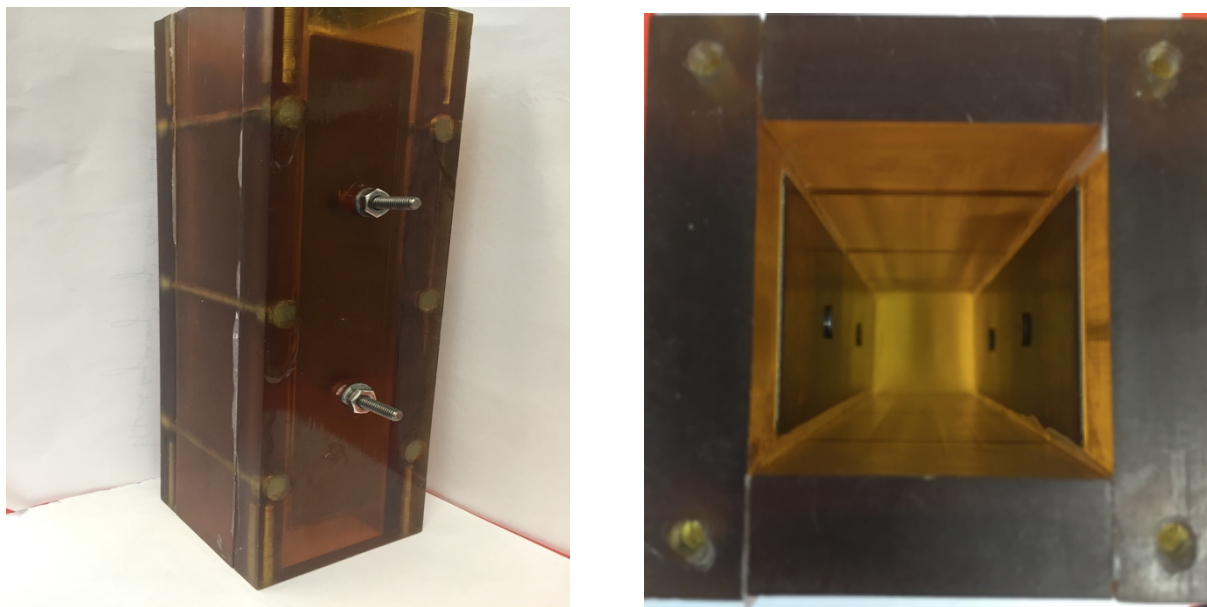
The basic configuration of the ohmic heating system is presented in Fig. 3.1. The system comprises with a variable voltage transformer (Bristol Gonn, USA), a rectangular ohmic cell coupling with two titanium plates as electrodes, and a data acquisition system (Agilent 34970A, USA) connected to a well calibrated 3-wire RTD temperature sensor, a current monitor (Pearson Electronics, Inc., USA), and a voltage monitor. The tip of the RTD sensor was located at the center of the ohmic cell, which touched the water first, and then the water and rice mixture, and close to the end of the rice layer. There were three sets of ohmic heating cells applied in this work consisting of the system for measuring electrical conductivity and that for cooking the rice samples. For the electrical conductivity measurement, the ohmic cell was made from a square tempered glass. The length of square electrodes was 4 cm, and the distance between electrodes was 4cm. For the rice cooking, in order to scale up the sample size, an ohmic cell was developed with a size of  $15 \times 6 \times 15 \text{ cm}^3$  was developed and coupled with a pair of stainless plates as electrodes (see Fig. 3.2). The distance between two electrodes was 6 cm. Another ohmic cell was made of Ultem with



a size of  $20 \times 6.7 \times 6.7 \text{ cm}^3$ . The distance between the two electrodes was 4 cm. A pair of titanium plates (5 grade corrosion- resistant) was used as electrodes and installed on both sides of the ohmic heating cell with dimension of  $17.2 \times 3.9 \text{ cm}^2$ .



**Fig. 3.1.** Schematic diagram of the ohmic heating apparatus



**Fig. 3.2.** Ohmic cell

During the experiments, the temperature sensor was inserted at the center of the rice-water mixture, and the temperature voltage and electric current were automatically recorded on the computer for further analysis. All experiments were done in triplicate unless stated otherwise. The experimental setup was similar to those of Engchuan. Jittanit, and Garnjanagoonchorn (2014), Jittanit and Khuenpet (2017), and Kanjanapongkul (2017).

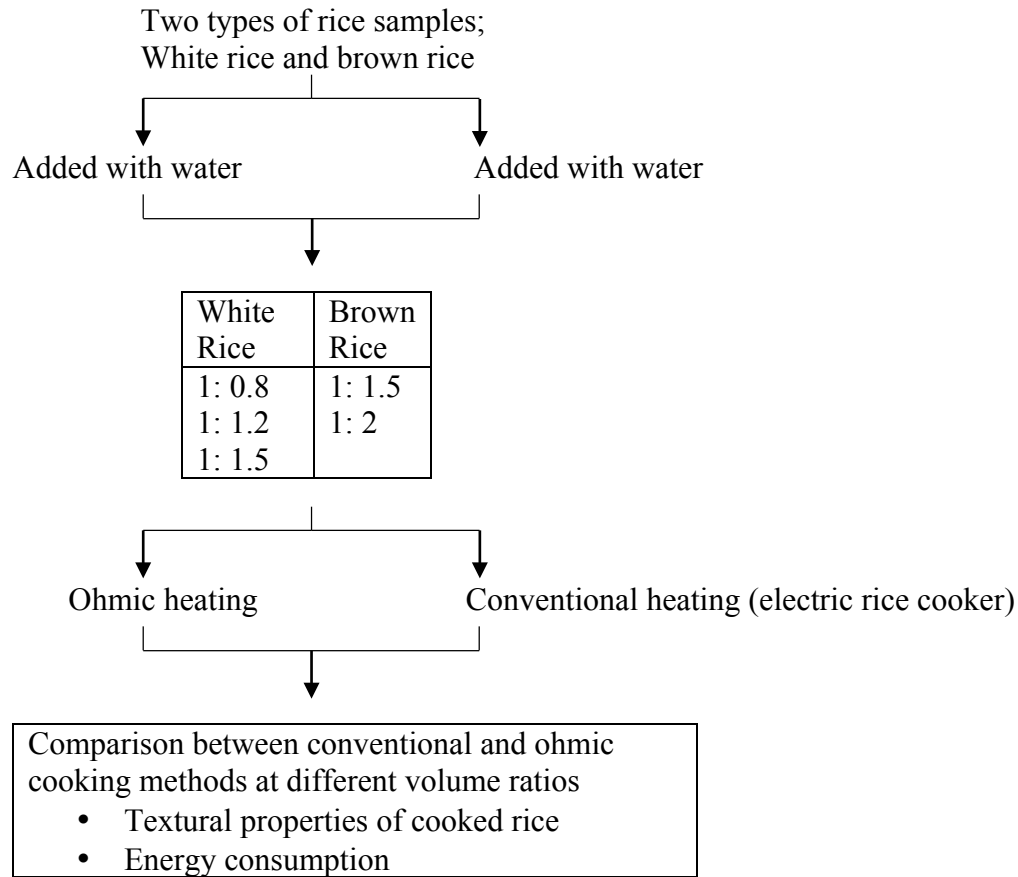
### **3.2.3 Determination of electrical conductivity of the mixture**

As previously mentioned, rice samples were added with the water. The volume ratios

between each sort of rice sample applied in this study are shown in Fig. 3.3. These volume ratios were specified by considering and analyzing the differences in rice quality by using the texture analyzer in this study. The electrical voltage applied between two electrodes was 140V with frequency of 50 Hz. The rice-water mixture was ohmic heated from room temperature around 25 to 100 degree at a constant electrical field of 35 V/cm. During the ohmic heating process, the temperature, electrical voltage, and current were recorded every 10 s by data acquisition model 34970A (Keysight Agilent, Santa Clara, California). A K-type thermocouple was inserted at the center of the ohmic cell and used for measuring temperature while the applied voltage and current were measured by a current monitor (Pearson, USA). During the electrical measurement, the thermocouple was placed into the water layer at the center of the water-rice mixture the inside of the rice kernel. The measurements were conducted in 3 replications. The electrical conductivity of mixture was calculated using equation (1):

$$\sigma \left( \frac{S}{m} \right) = \frac{LI}{AV} \quad (1)$$

where I and V are the electric current and voltage, respectively, while L, W, and H are the distance between electrodes, width and height of the mixture, respectively.



**Fig. 3.3.** Two types of rice-to-water volume ratios, the comparison of ohmic heating and conventional heating for rice cooking

### 3.2.4 Calculation of electrical energy consumption in the cooking process

The rice and water mixture was prepared at a ratio of rice grains to water of 1: 1.5 and 1: 2 (by the net volume) for white rice cooking and brown rice, respectively based on the normal proportions used in traditional rice cooking. The values of energy consumption were compared between cooking white rice and brown rice by electric rice cooker and ohmic heater. The electrical current and voltage were measured using the same method as previously mentioned in the section

of electrical conductivity measurement and recorded at each time interval of 10 s by Agilent data acquisition model 34970A. For each batch, the mass of rice grains was 2 cups, following the US standard of about 300 g. The mixture between rice and water was ohmic heated from room temperature (25 °C) and held at  $100 \pm 1^\circ\text{C}$  until the rice was completely cooked. The total energy consumption was the summation of electrical energy consumption values of all time intervals during the cooking process. The collected data were applied in the formula (2) for calculating energy consumption of ohmic heater.

$$E = VIt \quad (2)$$

where

E = Electrical energy consumption in each time interval (J)

I = Electrical current measured at each time interval (Ampere)

V = Applied voltage measured at each time interval (Volt)

t = Time interval (s).

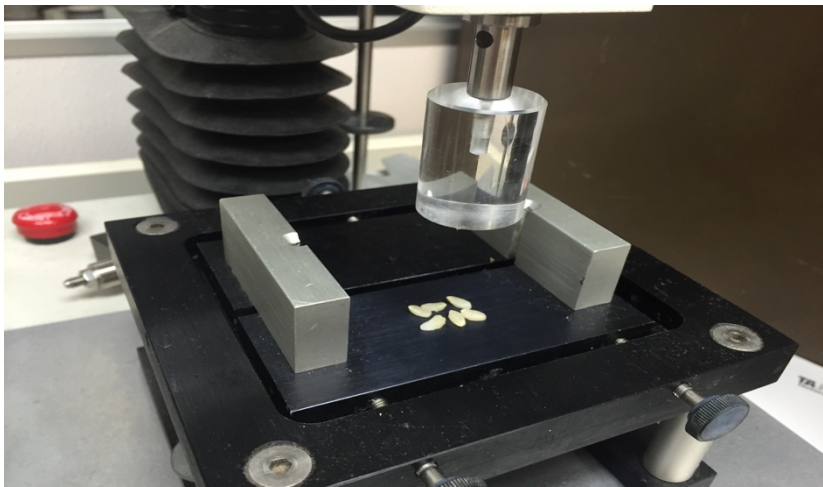
The rice-water mixtures were also prepared using the formula (2) and cooked using an electric rice cooker: A constant power electric rice cooker (rice cooker information). The totally energy consumed by electric rice cooker was calculated and compared with ohmic heating heater.

### **3.2.5 Textural qualities analysis of cooked rice samples**

The rice samples were cooked by the volume ratios of rice to water at 1:0.8, 1: 1.2, 1: 1.5, and 1:1.5, 1;2 for white rice and brown rice, respectively. A texture analyzer model TA. XT plus (Stable Micro Systems Ltd., Surrey, UK) was utilized to examine the texture of cooked rice samples. The method was modified by Jittanit et al., (2017), Miao et al (2016), and Soponronnarit (2016).

Kernel sampling methods (KSM) were used to select rice samples. After cooking, 6 intact rice kernels were randomly selected from top, middle and bottom layer, two rice grains for each layers. The rice samples were arranged in a single-grain layer on the aluminum base of the texture analyzer for each test (Fig. 3.4). This measurement was performed in triplicate by applying an acrylic cylindrical probe with a diameter of 1 inch, so that each type of rice sample was tested nine times at three different rice-to-water ratios. The samples were placed on the center of the clean flat aluminum base. A TPA (texture profile analysis) test was conducted, and the cylindrical probe was controlled to compress the samples to 90% strain for two cycles, with the test speed and post-test speed set at 1 mm/s.

The average values of hardness (HRD), adhesiveness(ADH), springiness (SPR), stickiness (STI), and chewiness (CHE) were determined.



**Fig.3.4.** Analysis procedure of rice texture using the texture analyzer

### **3.2.6 Electric field strength and temperature distribution analysis**

Electrical field distribution is important when designing the performance of the ohmic heating heater since it affects the heating uniformity and energy efficiency of the developed heater. Prior to the fabrication of the developed ohmic heating heater, detailed analyses of the electric field distribution inside the ohmic heater at stationary state were conducted by using SolidWorks software (SolidWorks Corporation, United States), including various modules for specific applications. The results for ohmic heater were obtained from the Conductive Media DC Module with parallel direct sparse solver (PARDISO). Simulation for ohmic heating was conducted using multiphysics software (COMSOL 4.6, COMSOL Inc., Palo Alto, CA) based on the finite element method (FEM).

### **3.2.7 Statistical analysis**

IBM SPSS Statistics Edition 23 was used for the analysis of variance (ANOVA) and regression equation in the statistical analysis.

## **3.3. Results and discussion**

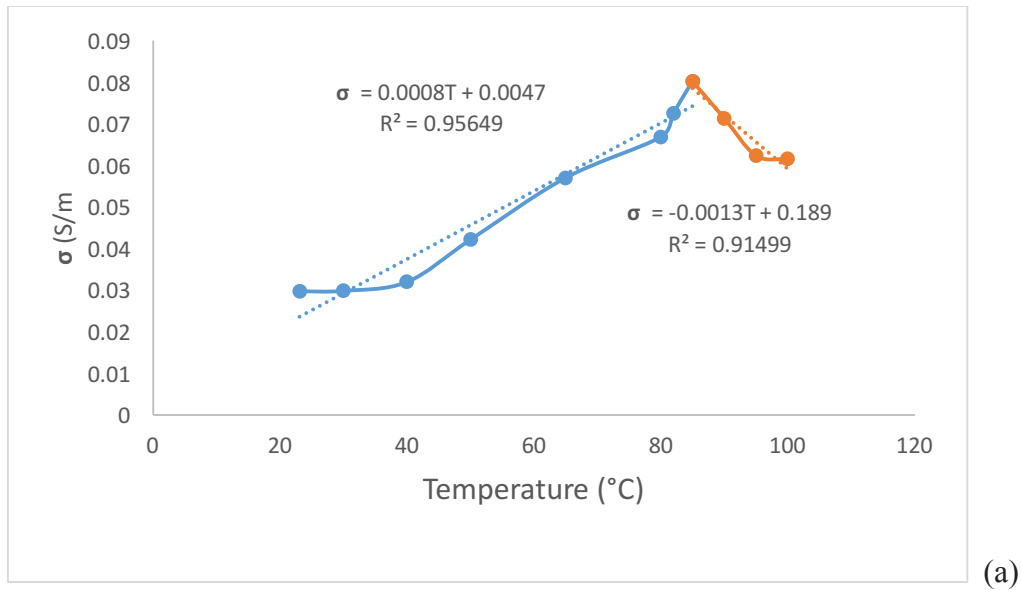
### **3.3.1. Electrical conductivity of rice and water mixtures**

Fig. 3.5a shows the electrical conductivity of the rice-water mixture (water/grain mixing ratio of 1:0.8) during ohmic heating as a function of temperature. The change in electrical conductivity and temperature was observed at the transition temperature about of 80 °C. There is a linear relationship between the electrical conductivity of rice-water mixture and temperature, which is expressed using equation (3) and (4):

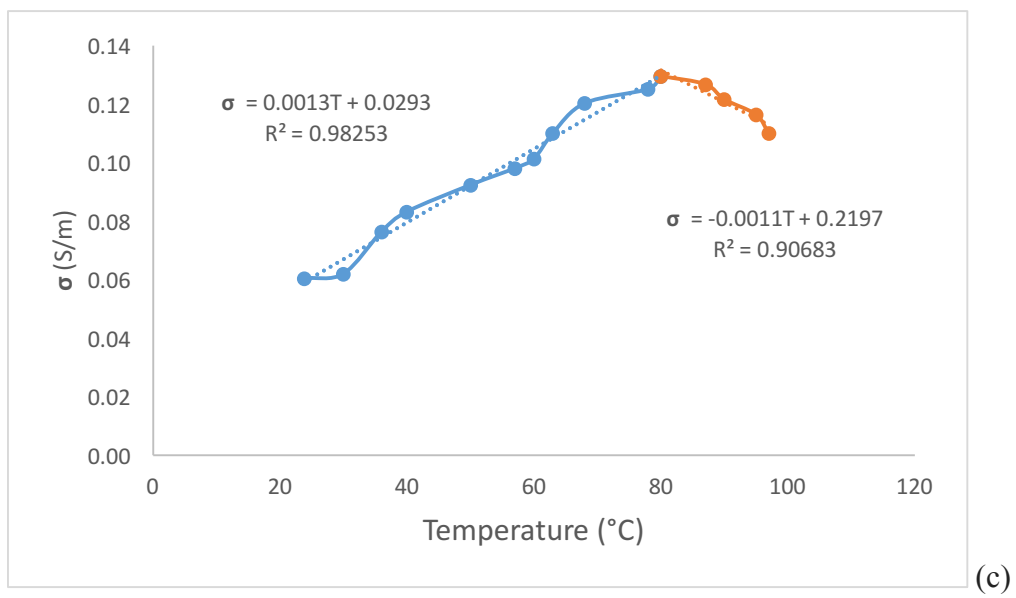
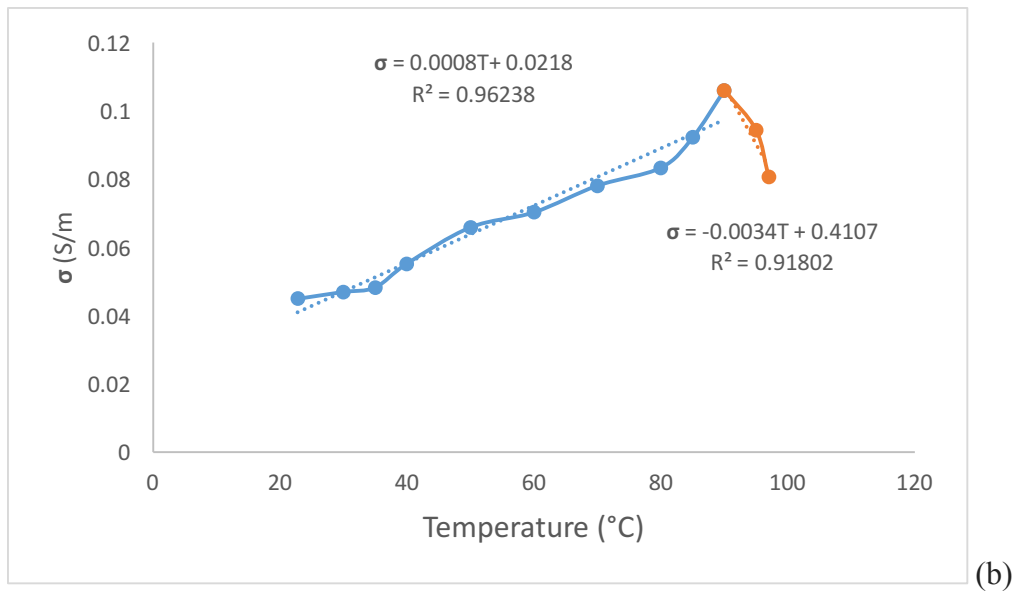
$$\sigma = 0.0008T + 0.0218; 23 < T < 80 \quad (3)$$

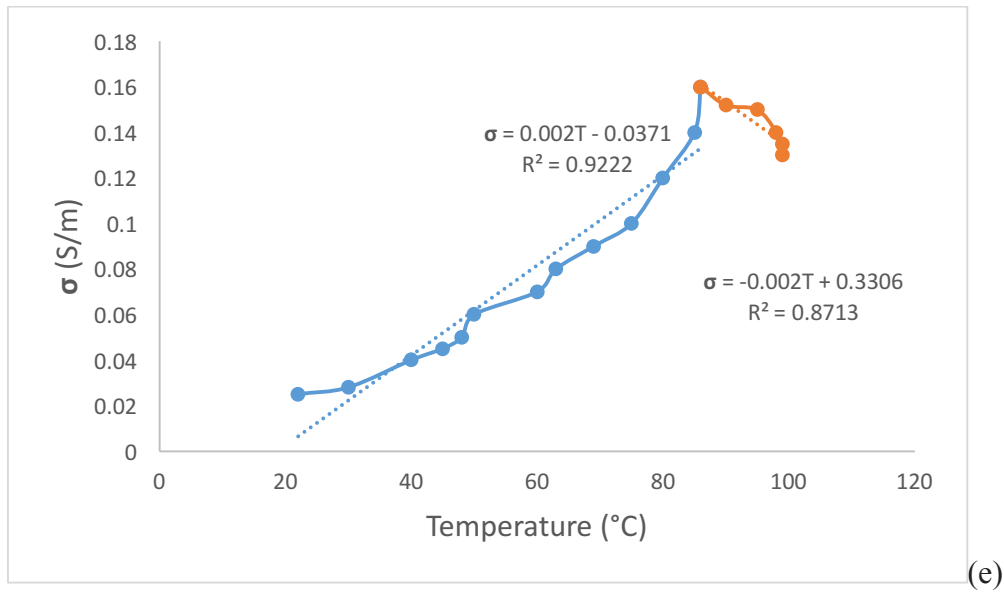
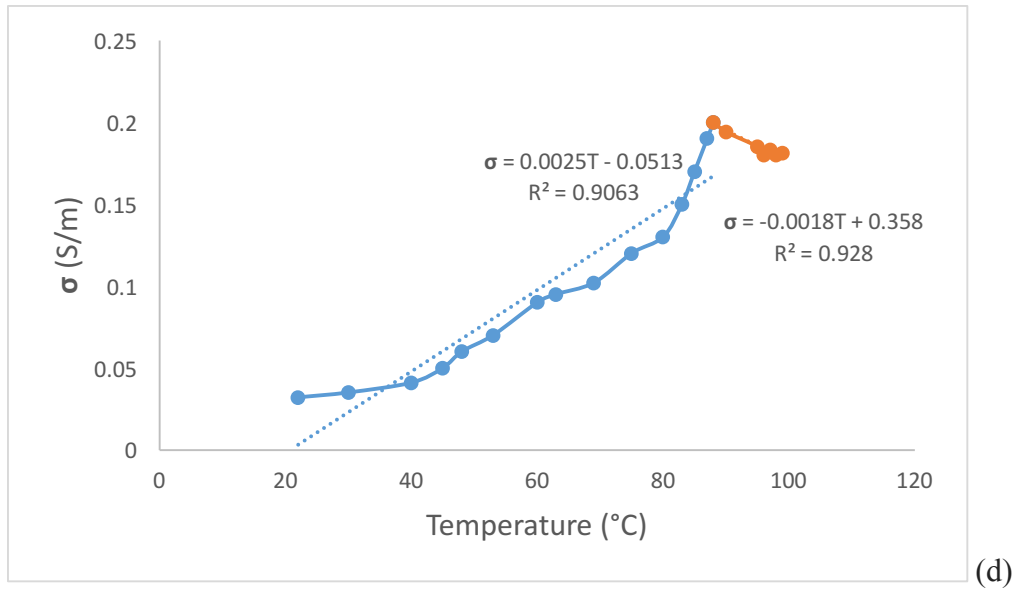
$$\sigma = -0.0034T + 0.4107; T \geq 80 \quad (4)$$

Also, all the equations for predicting the electrical conductivity of rice samples at different rice to water volume ratios as a function of temperature were developed as shown in Fig. 3.5 (a-e) by fitting the experimental data into the mathematical model. The model fitting was performed by a least square method using the SPSS Edition 23. The measured electrical conductivity data would be useful for evaluating the possibility of applying ohmic heating method for the white rice and brown rice at the cooking condition of low water usage. Moreover, these data would be the database for utilization by either researchers and the industry.









**Fig.3.5.** Electrical conductivity of white rice-to-water volume ratio at 1: 0.8 (a), 1: 1.2 (b), 1: 1.5 (c) and electrical conductivity of brown rice-to-water volume ratio at 1: 2 (d), and 1: 1.5 (e).

In this study, a pre-estimation of the electrical conductivity of rice grains is important in order to properly design an ohmic heater for rice cooking. However, it was difficult to measure the

electrical conductivity of rice grains. The electrical conductivity of mixtures of rice and water at different rice-to-water ratios was determined. The results of electrical conductivity measurements for the mixtures of rice samples at different volume ratios were illustrated in Fig. 3.5 (a-e) as a function of temperature. It showed that the electrical conductivities of rice samples were approximately 0.03-0.08, 0.04-0.1, 0.06-0.12 S/m for white rice at volume ratios of 1:0.8, 1:1.2, 1:1.5, respectively, and 0.025-0.16 S/m for brown rice at volume ratios of 1:1.5 and 0.032-0.2 for a volume ratio of 1:2, indicating that it is possible to apply the ohmic heating technique for cooking of those two kinds of rice samples due to their suitable electrical conductivity. The graph evidently illustrated that the electrical conductivity of rice samples slightly increased at the beginning of the time period when the temperature was under the 30 °C. When the temperature was about 30-85 °C, the electrical conductivity increased along with the rising temperature. According to Sarang and Satry (2008), the electrical conductivity of most foods increases linearly with the climbing temperature. Icier and Ilicali (2005) point out the movement of ions within the rice-water mixture is accelerated, resulting in an increase in electrical conductivity when the sample temperature is boosted. However, the tendency of the electrical conductivities of all samples in this study was to decrease significantly after reaching a temperature of about 80-90 °C. The phenomena called “block peak” and should be related to starch gelatinization, which happened at the temperature between 55 and 79 °C depending on the rice variety (Roy et al., 2010). During the rice cooking process, when the rice-water mixture temperature increased to the starch gelatinization temperature, the starch granules in the rice were broken down under the needed energy and moisture and leaked into water. According to Jittanit et al; (2017), the starch gelatinization process continued and influenced the electrical conductivity until the sample was fully gelatinized. Similar results were reported from Karapantsios et al; (2000), who stated that during the heating process

of starch, the electrical conductivity rose with temperature until the gelatinization temperature. The reduced electrical conductance was observed at the end of starch gelatinization. Li et al. (2004) found that the electrical conductivity of starch-water mixture was increase linearly with temperature except for the gelatinization range. The reason related to the decrease of electrical conductivity was that the area for motion of charged particles was declined since the swelling of starch granules during gelatinization. Moreover, the starch granules absorbed water and swelled during gelatinization, which lead to the decrease of free water (Wang and Sastry,1997).

It was noticed that the electrical conductivities of brown rice were higher than those of white rice samples. The probable explanation is that the milling degree of white rice was adequately polished to remove the bran layer and germ that contain some ions and nutrients (Ohtsubo et al., 2005). Moreover, the brown contains more iron than white rice. These ionic components cause the higher electrical conductivity of brown rice. Moreover, the more water was added to brown rice, which contains free ions. However, with the temperature at 30-80 °C, the white rice had a faster heating rate than brown rice under the same rice-to-water volume ratio. However, the brown rice had higher electrical conductivity than that of white rice. It could be explained that the heating rate also dependent on thermal properties of food materials such as specific heat, thermal conductivity, and thermal diffusivity.

### **3.3.2 Rice cooking by ohmic and conventional heating methods**

White rice and brown rice were successfully cooked by ohmic heating. Fig. 3.6 (a) shows the appearance of the rice which were similar to the rice cooked using an electric rice cooker. After the heating treatment, we observed that a rice layer stuck to the bottom of the container in the rice

cooker. See Fig. 3.6. (b). In an automatic electric rice cooker, the heater generates heat under the container, heat is transferred from the heater to the liquid in the food sample via conduction, and then the heat is transferred to the rice by convection. The whole heat transfer process was generated from the bottom up on the container; thus, the temperature at the bottom of the container was the highest, and the rice grains in contact with it could become burnt. In contrast, no rice layer fouled or deposited on the ohmic cell was observed because no hot surface was created due to the internal heat transfer concept in ohmic heating. Table. 3.1, compares cleaning methods for ohmic heating and conventional heating methods after the rice was fully cooked. It is unsurprising that the ohmic cell was easier to clean than the conventional container by rinsing it with water. Similar results were found by Kanjanapongkul, (2017).

(a)

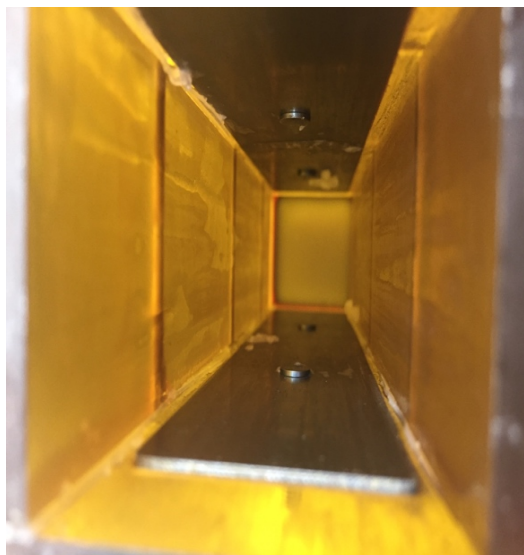


Rice cooker



Ohmic heater

(b)



Ohmic



Conventional

**Fig. 3.6.** The appearance of cooked rice by ohmic and rice cooker (a) and the comparison of ohmic and conventional container (b)

**Table. 3.1.** Comparison of cleaning method after rice cooking

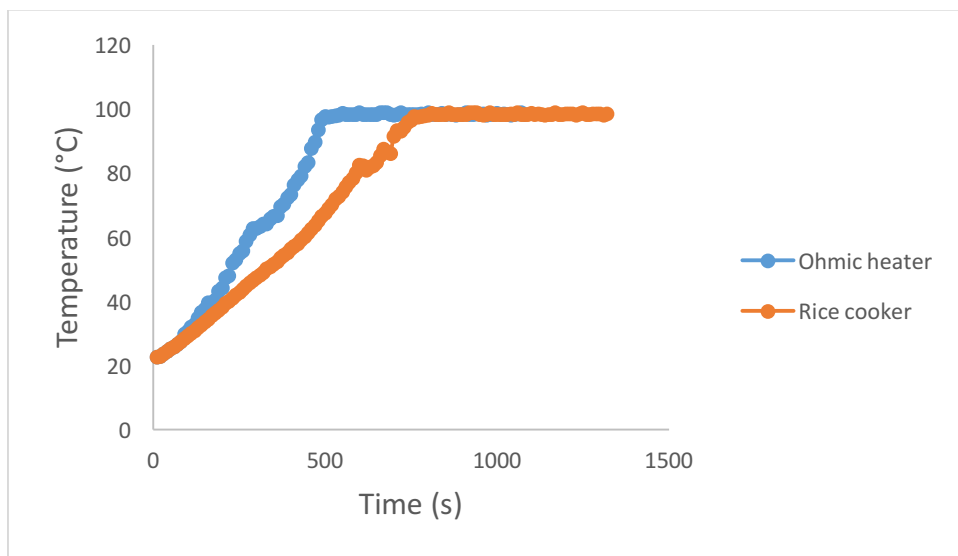
Cooking method	Cleaning methods	Time	Water cost	Cleanness
Ohmic heating	water rinse	-	-	++
Conventional heating	water rinse	- - -	- -	+

+: satisfactory, - : unsatisfactory

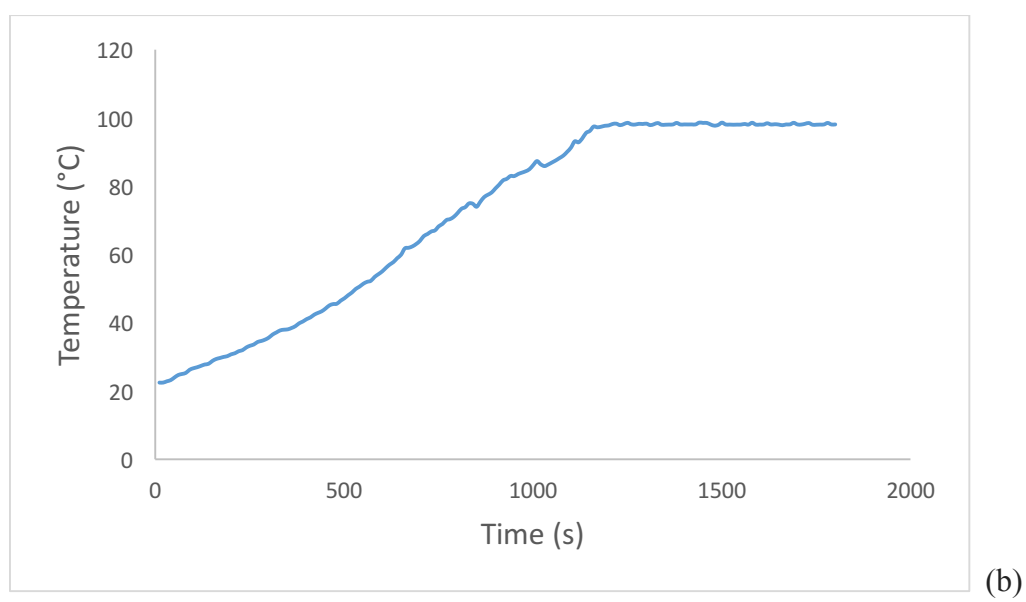
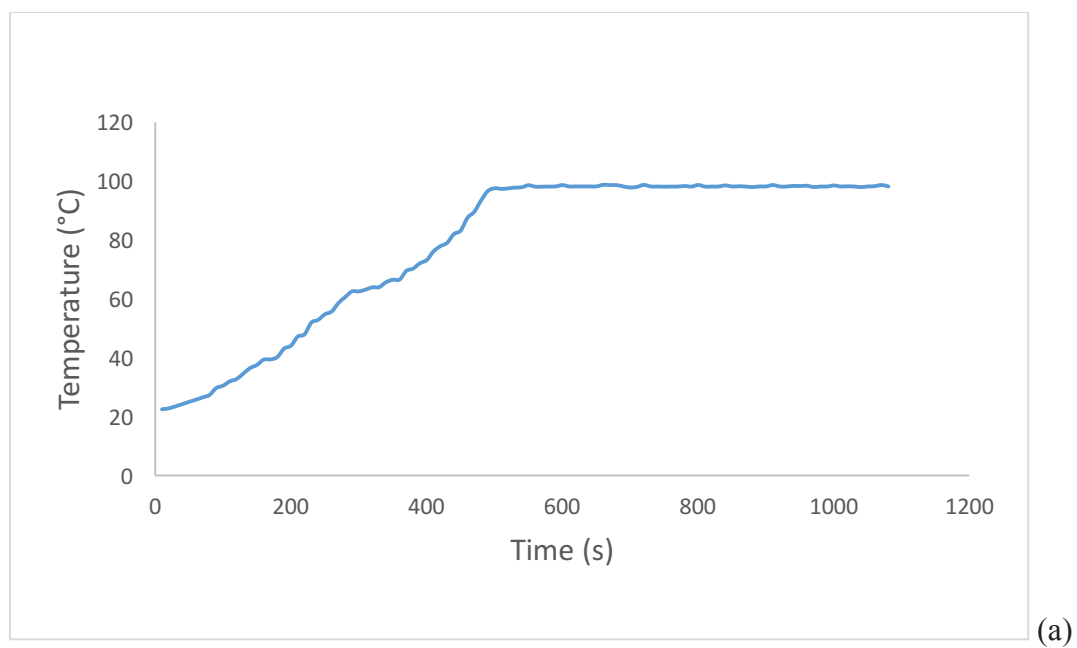
As seen in Fig. 3.7., it was found that the cooking time required by the ohmic cooker was about  $17.4 \pm 1.1$  min and  $27 \pm 1.2$  for white rice and brown rice, respectively, under an electrical field strength of 35 V/cm, while the cooking time required by the electric rice cooker was nearly

constant at  $22.2 \pm 0.8$  min and  $32.1 \pm 1.1$  min for white rice and brown rice, respectively. Fig. 3.8 shows that the cooking time needed for the ohmic heater was dependent on the electric field strength. Under the low and medium electric field strengths (20, 30, 35 V/cm), the cooking times for white rice were about  $32.3 \pm 1$  min,  $22.1 \pm 1.2$  min,  $17.4 \pm 1.1$  min respectively. The results illustrated that the cooking time required by ohmic heating was slightly shorter (17 and 27 min). The finding is that ohmic heating could reduce cooking time if the electric field strength was above 35 V/cm which is very useful for the design of the ohmic rice cooker.

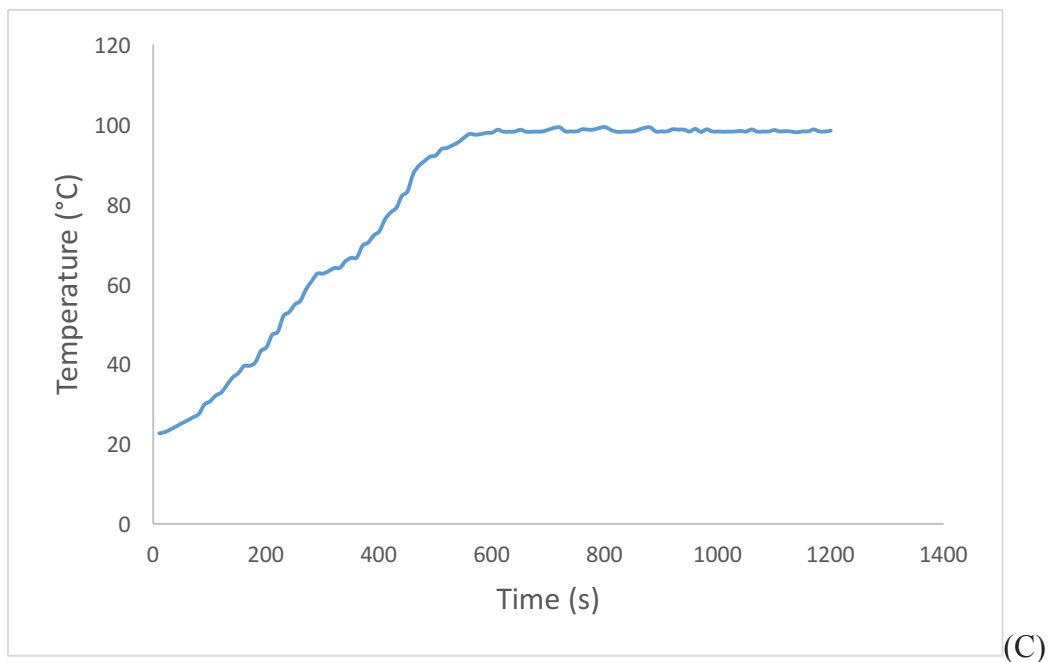
When comparing between ohmic heater and electric rice cooker, the rice sample temperature profiles during ohmic heating were controlled to be similar to those of conventional heating method in order to investigate the rice textural quality of the rice and energy consumption without intervention. In reality, the appliance of ohmic heating required 7 or 8 min from room temperature to 100 °C and finished the rice cooking around 17 min. However, the electric rice cooker needed 12 or 13 min to reaching the temperature of 100 °C and fully cooked the rice around 22 min (see Fig. 3.7).



**Fig. 3.7.** Temperature profiles of samples during cooking





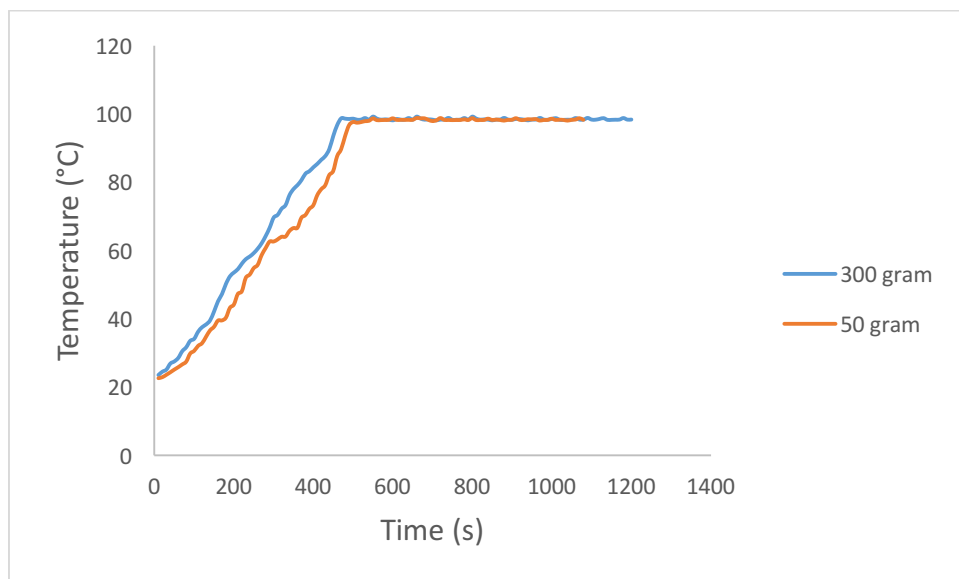


**Fig. 3.8.** Temperature profile under 35 V/cm (a), 25 V/cm (b) and 30V/cm (c)

### 3.3.3 Identification of end point of cooking

The end point of rice cooking by using ohmic heating was identified by using the method modified from parallel glass plate method as proposed by Desikachar and Subrahmanyam (1961). In this method, the rice samples periodically drawn out when there was no water observed in the ohmic cell and were pressed in between two small glass plates. If there was no hard and white core observed, the sample was considered to be completely cooked. In the study of Das et al, (2006) used the parallel glass plate method to determine the end point of rice cooking in a domestic rice cooker. The method modified from Desikachar and Subrahmanyam (1961) was used as a quick test and for confirmation that rice had been fully cooked. A new ohmic cell was developed to increase the sample rice. According to Fig. 3.9, it is unsurprised that the scaled ohmic cell had a similar

temperature profile with small ohmic cell for 300 and 50 grams white rice cooking respectively under 35 V/cm.



**Fig. 3.9.** Temperature profile under two sample size

### 3.3.4 Textural qualities of cooked rice

Texture is an important attribute of cooked rice and has been used as an indicator for consumer acceptance. Several factors influence the rice texture such as the rice variety, amylose content, gelatinization temperature as well as the cooking condition including the water/rice ratio. The rice specimens that were cooked by suitable volume ratios of rice to water (1:0.8, 1:1.2, and 1:1.5 for white rice, and 1:1.5, and 1:2 for brown rice, respectively) were subjected to the TPA (texture profile analysis). The textural attributes of rice samples cooked by electric rice cooker and ohmic heating method are presented in the Table. 3.2. The results illustrated that the ohmic heating significantly affected the texture quality of the cooked rice samples. It appeared that the white rice cooked by the electric rice cooker had the higher hardness values than those of cooked by the

ohmic heating method. The textural attributes were influenced by various factors, including the type of rice, amylose content, gelatinization temperature, and cooking condition (Meullenet et al., 1998). In this study, it was observed that the white rice cooked by ohmic heating had a lower value of hardness than that cooked through the conventional heating method. The reason may be that the temperature distribution inside the water and rice mixture is more uniform due to the internal heating generation concept. Thus, the rice grain would be gelatinized throughout the kernels simultaneously. In the electric rice cooker, the heat is transferred from bottom to up by conduction and convection. As a result, the gelatinization would start and begin from the outer layer of the rice grain to the center of rice kernels, so that conventional heating method results in a harder structure of the cooked rice. According to Huang and He (2013), the high degree of gelatinization leads to the result of a soft texture with cooked rice. Kanjanapongkul (2017) pointed out that the use of an electric field in ohmic heating enhanced the water diffusion into rice grains. Jittanit (2017) pointed out the rice cooked by ohmic heating had a greater level of gelatinization than conventionally cooked rice. The structure of rice cooked by ohmic heating is usually more porous than that of the conventional heating method because of the one typical characteristic of ohmic heating; electroporation of cell membranes. According to An and King (2007), and Lima and Sastry (1999), electroporation is the formation of pores in cell membranes due to the application of an electric field, resulting in permeable cell membranes and involves the increased diffusion of water.

The hardness of brown rice was the highest among the specimens. It should be caused by its high amylose content and big size of amylose molecules. According to the Li et al., (2016), the proportion of amylose branches and the size of amylose molecular significantly was mainly affect the hardness. It appeared that the white rice cooked by a ratio of 1:1.5 rice to water was softer than

that cooked by 1:1.2 and 1:0.8 ratios. The explanation was that the greater amount of water was added required longer cooking time.

**Table. 3.2.** Textural attributes of conventional and ohmic heating methods

Rice type	Cooking method	Hardness (N)	Chewiness (N)	Adhesiveness (mJ)	Springiness (N)	Stickiness (N)
WR 1/0.8	OH	49.426 <sup>b</sup> ±1.434	30.506 <sup>b</sup> ±0.421	-2.312 <sup>c</sup> ± 0.256	0.281 <sup>ab</sup> ±0.012	-5.673 <sup>b</sup> ±0.851
	RC	58.722 <sup>a</sup> ±3.216	35.106 <sup>a</sup> ±1.731	-3.270 <sup>c</sup> ± 0.175	0.245 <sup>b</sup> ± 0.031	-1.772 <sup>a</sup> ±1.241
WR 1/1.2	OH	44.934 <sup>bc</sup> ±2.132	32.385 <sup>b</sup> ±0.912	-1.666 <sup>b</sup> ±0.076	0.287 <sup>ab</sup> ± 0.02	-6.876 <sup>bc</sup> ±1.721
	RC	55.372 <sup>a</sup> ±1.426	34.934 <sup>a</sup> ±1.431	-2.862 <sup>d</sup> ±0.248	0.315 <sup>a</sup> ± 0.041	-2.388 <sup>a</sup> ±1.132
WR 1/1.5	OH	39.527 <sup>c</sup> ± 3.218	28.421 <sup>c</sup> ±0.751	-1.237 <sup>a</sup> ± 0.121	0.325 <sup>a</sup> ± 0.036	-8.12 <sup>c</sup> ± 0.962
	RC	50.876 <sup>b</sup> ±5.121	31.633 <sup>b</sup> ±0.832	-2.377 <sup>c</sup> ± 0.086	0.295 <sup>ab</sup> ±0.021	-2.472 <sup>a</sup> ±0.622

Means with same superscript with same column are insignificant different ( $P > 0.05$ )

Rice type	Cooking method	Hardness (N)	Chewiness (N)	Adhesiveness (mJ)	Springiness (N)	Stickiness (N)
BR 1/1.5	OH	58.487 <sup>b</sup> ±2.313	34.212 <sup>b</sup> ±2.131	-2.974 <sup>ab</sup> ±0.093	0.257 <sup>a</sup> ±0.021	-0.872 <sup>a</sup> ±1.354
	RC	69.211 <sup>a</sup> ±4.215	38.512 <sup>a</sup> ±1.342	-3.452 <sup>c</sup> ±0.342	0.225 <sup>a</sup> ±0.041	-0.455 <sup>a</sup> ±0.897
BR 1/2	OH	55.284 <sup>b</sup> ±2.412	33.894 <sup>b</sup> ±1.564	-2.723 <sup>a</sup> ±0.235	0.281 <sup>a</sup> ±0.032	-0.895 <sup>a</sup> ±1.452
	RC	65.612 <sup>a</sup> ±1.893	37.324 <sup>a</sup> ±1.566	-3.362 <sup>bc</sup> ±0.176	0.231 <sup>a</sup> ±0.054	-0.588 <sup>a</sup> ±0.942

Means with same superscript with same column are insignificant different ( $P > 0.05$ )

### 3.3.5 The electrical energy consumption and the cooked rice appearance

Table. 3.3 shows the energy consumption of white rice cooked by conventional and ohmic heating methods. From the data recorded during rice cooking experiments of white rice in the electric rice cooker, it appeared that the electrical voltage was rather constant at around 220 V, while the average of current value was 2.34 ampere. For the ohmic heater, the both values of voltage and current varied all the time during the ohmic cooking process. The energy consumption of the conventional heating method was estimated by applying the constant value of voltage and average value of current with the total cooking time into the previously mentioned formula (2). However, the total energy consumed by ohmic heating was calculated by the applied voltage and current recorded at each time interval. Lastly, the energy consumption of all the time intervals were summed up to show the total energy consumption. It was found that the cooking energy required by the ohmic heating process was about 1/4 of the total energy consumed by the AROMA Simply Stainless rice cooker. The ohmic heater consumed less energy compared to the rice cooker used in this research. From the calculation of the amounts of total energy required for rice cooking process, the ohmic heater requires 95.48 KJ while the rice cooker was 364.48 KJ (for 300 grams of rice cooking). The comparison of electrical energy cost between the ohmic heater and the rice cooker was 1.38 USD/day and 1.82 USD/day, respectively. It would be a huge energy saving if this technique for rice cooking would be applied by the world's population. It is not surprise that the advanced ohmic heating method found in this study consumed significantly less energy consumption than the electric rice cooker. The reason was that the ohmic heating is 100% energy efficient which called direct heating. Basically, the heat was generated from the inside to the outside of the food samples. On the other hand, the electric rice cooker generates heat by converting electrical energy to be thermal energy at heating plates, and then the heat is transferred

to the container and mixture of water and rice by conduction and convention. The several steps of heat transfer lead to the loss of energy and subsequent decrease of thermal efficiency of cooking system.

**Table. 3.3.** Electrical energy consumption of White rice cooked by conventional and ohmic methods.

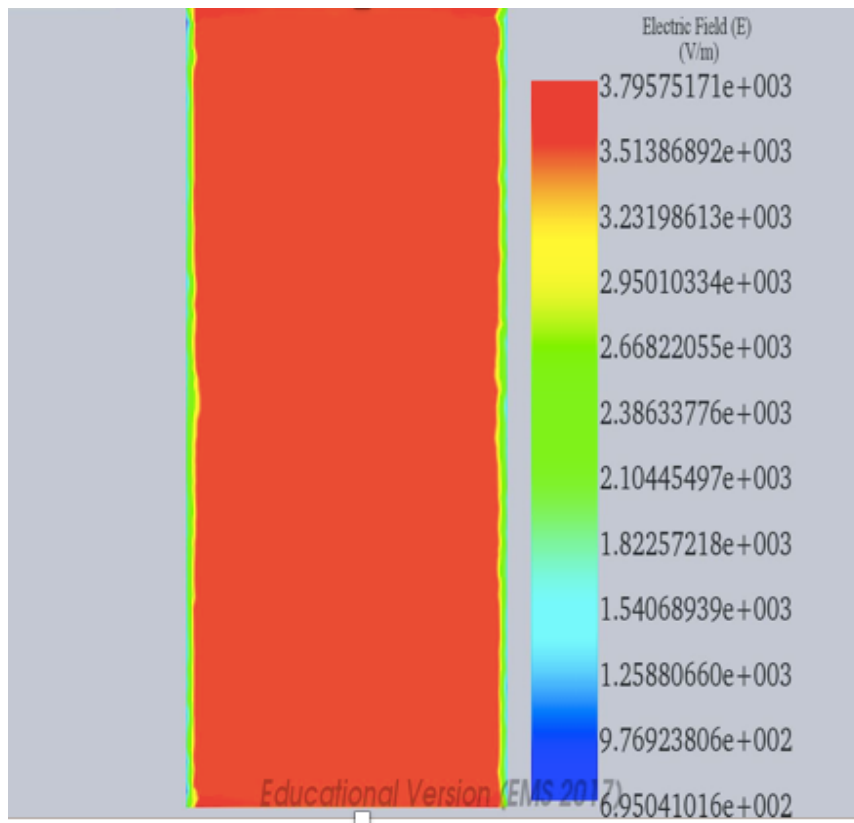
<b>Rice type</b>	<b>Cooking method</b>	<b>Applied voltage</b>	<b>Electrical current (ampere)</b>	<b>Cooking time (minute)</b>	<b>Electrical energy consumption (KJ)</b>	<b>Electrical energy cost (USD)</b>
<b>White rice</b>	<b>Ohmic heating</b>	<b>128-149</b>	<b>0.1-0.68</b>	<b>22</b>	<b>95.48</b>	<b>0.008</b>
	<b>Conventional</b>	<b>118</b>	<b>2.34</b>	<b>22</b>	<b>364.48</b>	<b>0.033</b>

Note: The unit price of electricity in the United States, Hawaii, was approximately 0.33 USD/KWh.

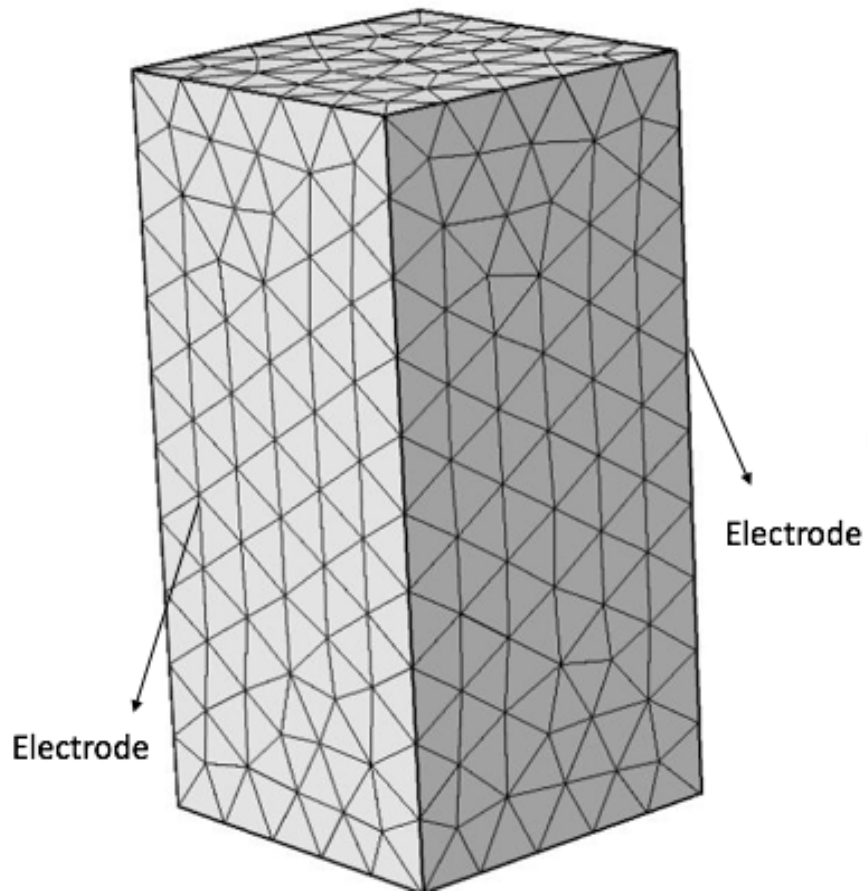
### 3.3.6 Simulated electric field under ohmic heating

Fig. 3.10 shows the electric field distribution under the process of rice cooking in ohmic heating simulated using SolidWorks, when 140 V as an applied voltage. The electric field strength simulated for the ohmic cell ranged between 23.39 and 40.94 V/cm. Although even electric field distribution was observed at the rages of between two electrodes. The E field strength at the corner of top and bottom corners relatively high. According to Lee et al., (2015), the localized field overshoot occurring at both side edges of the electrodes can result in numerous problems, such as the corrosion through electrochemical reactions at the edges of electrodes in the ohmic heating system. Nguyen et al., (2013) reported that the performance of ohmic heaters was not significantly influenced by localized field overshoots. The mixture temperature increased rapidly with ohmic

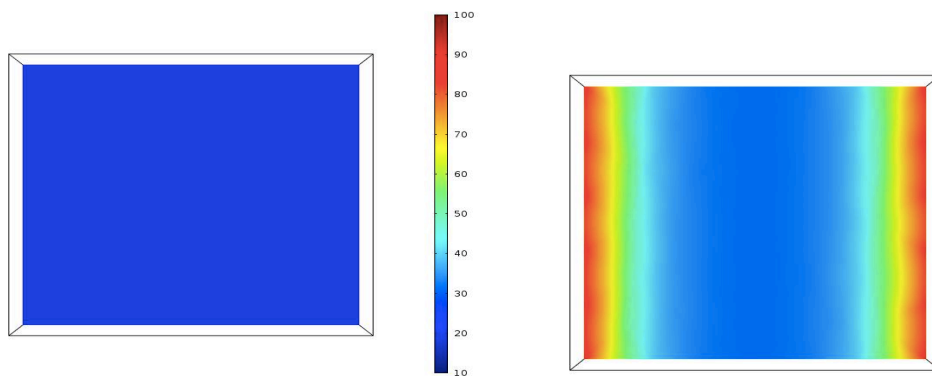
heating treatment (Fig.3.11). After 60 s, most part of the sample showed a temperature distribution of 20 ~ 30 °C. However, only the corner of the sample reached temperatures of approximately 60 °C. When the center of the sample reached temperature of 90 °C, the times to reach the hot point was 360 s.



**Fig. 3.10.** Electric field distribution in the ohmic heater



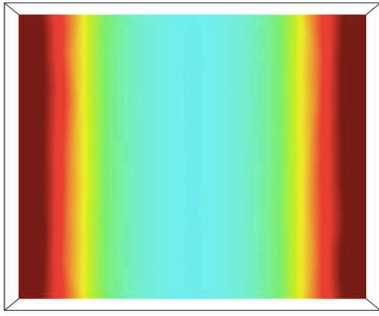
**Fig. 3.11.** 3D tetrahedral mesh domain



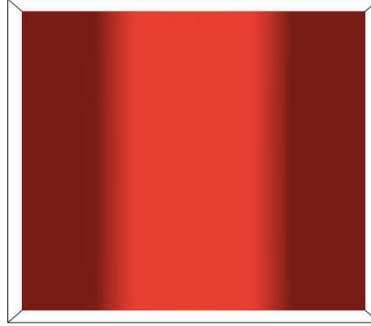
(a) Time = 0 sec

(b) Time = 60 sec

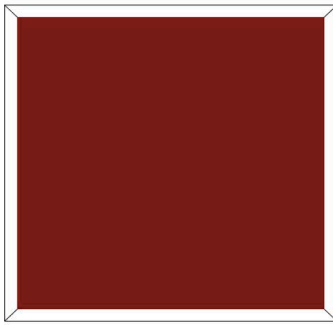




(c) Time = 120 sec



(d) Time = 300 sec



(e) Time = 360 sec

**Fig. 3.12.** Simulation results of the temperature distribution during ohmic rice cooking:

(a) time = 0 sec, (b) 60 sec, (c) 120 sec, (d) 300 sec and (e) 360 sec.

### 3.4. Conclusion

To sum up, all results of this study positively suggested that it is possible to apply ohmic heating as an attractive alternative cooking method for the cooking of white rice and brown rice. Regarding the rice to water volume ratio, it is possible to decrease the volume ratio to 1:0.8 for

white rice and 1:1.5 for brown rice, respectively, without any textural quality influence. The relationship between the electrical conductivity of the rice and water mixture and temperature could be described by a two-step linear equation. The rice variety, starch gelatinization, and the rice-to-water volume ratio should be taken into account when designing the ohmic heating cooker since the starch gelatinization causes a decrease in the electrical conductivity of the water-rice mixture. The rice cooked by the ohmic method had textural properties significantly different from that cooked by the electric rice cooker, for example, hardness. There were no significantly different textural properties found in white rice prepared by 1:0.8 and 1:1.2 rice to water volume ratios and 1:1.5 and 1:2 volume ratios for brown rice. The estimated amount of energy consumed by the entire ohmic heating process was about 1/4 of the total energy consumed by electric rice cooker. In addition, there was no rice burnt and fouling observed on the ohmic container after rice cooking was completed because the heat was generated from the inside to the outside of the rice grain.

### **3.5. Future study**

Ohmic heating requires pre-estimation of electrical conductivity. It is necessary that food samples had suitable conductivity in order to heat up in the ohmic cooker. The method of increasing electrical conductivity should be developed without sensory influence. For example, the salt solution added was successful increase the electrical conductivity; however, it totally changed the food taste. For future rice cooking, the ohmic heating could be combined with other existing heating methods, such as, microwave heating in order to overcome the drawbacks of ohmic heating. The combination heating method should be investigated.

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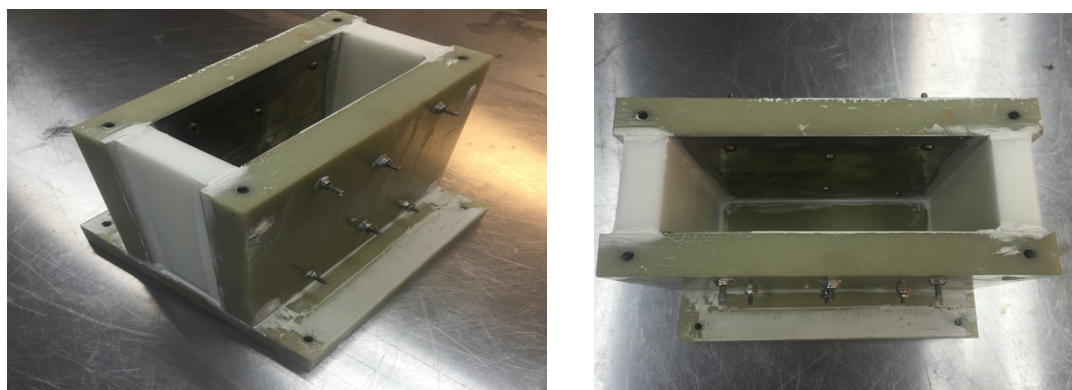
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## CONCLUSION & FUTURE STUDIES

The three main objectives of this thesis was fulfilled adequately. Firstly, the study proved that it is possible to create a cost efficient scaled up ohmic cell for rice cooking. Second, the ohmic heating system was able to demonstrate its capability to cook white rice at 1:0.8, 1: 1.2, 1: 1.5 and brown rice at 1: 1.5, 1: 2 volume ratios, respectively, thereby providing that the results show that the rice cooked by ohmically heating had significantly different textural properties from rice cooked by the conventional heating method. The temperature and electric field distribution were simulated and analyzed. Lastly, the relationship and the effect of three parameters (voltage, volume ratio, rice variety) influencing the cooking process was examined and analyzed sufficiently. The electrical energy consumption of ohmic heating was approximately 25-35% less than the energy required for a conventional rice cooker. All these findings positively support ohmic heating's potential as an alternative to cooking rice.



**Fig. 4.1.** The scaled-up ohmic cell coupled with two titanium electrodes.

For future studies, various rice must be selected to represent the abilities of the ohmic heating system to cook the rice. There is consideration regarding the potential electrochemical reactions at the contact surface between the electrodes and food during ohmic heating. Therefore, an anti-fouling functional ohmic heating system must be designed to prevent oxidation reactions and metallic contamination of the food product. The prevention of corrosion on electrodes can be achieved with alternating current at frequency values greater than 20 KHz, due to the reversed field effect. Moreover, the nano-engineered surface has successfully prevented the adhesion of bacteria due to its super hydrophobic surface. The surface coating on the electrodes could be developed as an effective way to prevent the undesirable electrochemical reactions in future studies. Lastly, it is necessary to pre-estimate the electrical conductivity of food product. The determination of electrical conductivity is a prerequisite to ohmically heated particulate foods. For this reason, the microwave and ohmic combination heating method could be applied to simultaneously cook a rice/water mixture.